LA-UR-17-30765

Title: Helmet Heat Exchanger Thermal Final Report

Author(s): Lucero, Briana
Cage, Kailyn
Spernjak, Dusan
Bernardin, John David

Intended for: Report

Issued: 2017-11-28

Helmet Heat Exchanger Thermal Final Report

Briana Lucero, Kailyn Cage, Dusan Spernjak and John Bernardin

AET-1

Systems Design Phase – Proof of Concept

HELMET HEAT EXCHANGER

Helmet heat exchanger requirements

ID number	Requirement	Verification Method
HVHE1	The HE shall fit on the helmet ranging from 0.2131m^2 to 0.85228m^2.	Inspection
HVHE2	The system shall not impede the visibility of the operator by providing at least 95 % FOV.	Test
HVHE3	Integration of the heat exchanger/helmet shall not compromise the structual performance integrity of the helmet.	Analysis
HVHE4	The system shall operate in the Intermediate temperature environmental conditions called out in Table C-I of MIL-STD-810 with no less than 60% degradation at a maximum of 40 % R.H. • 28-39 deg C	Test, Analysis
HVHE5	The system shall be able to operate in the Environmental Stress Generation Mechanisms called out in MIL-STD-810: • high temperatures at dry/humid conditions (max 49 deg C, R.H. 3%-59%) • low temperatures at dry/humid conditions (min 5 deg C, R.H. 3%-30%)	Test, Analysis
HVHE6	The system shall have an operations lifespan of [TBD] months after anticipated [TBD] months of storage/transport.	Analysis
HVHE7	The heat exchanger shall integrate in to the procured PASGT GI helmet with less than 1 hour of integration work.	Demonstration
HVHE8	The HW shall be able to withstand forces up to [TBD] N sustained and [TBD] N point force impact.	Analysis
HVHE9	The HE shall operate passively without external power sources.	Demonstration
HVHE10	The HE shall dissipate heat at a rate of 2 W/m^2/hr passively	Test, Analysis
HVHE11	The interior helmet temperature shall be no more than 35 deg C	Test, Analysis
HVHE12	The exterior helmet temperature shall be no more than 50 deg C	Test, Analysis
HVHE13	The HE shall have an operating temperature of no greater than 35 deg C.	Test, Analysis
HVHE14	The HE shall operate at 90% effectiveness in the temperature range of 25 to 35 deg C.	Test, Analysis
HVHE15	The HE design shall be no larger than [TBDX] x [TBDY]x [TBDZ] m (dimensions), weigh more than [TBD] kg.	Demonstration

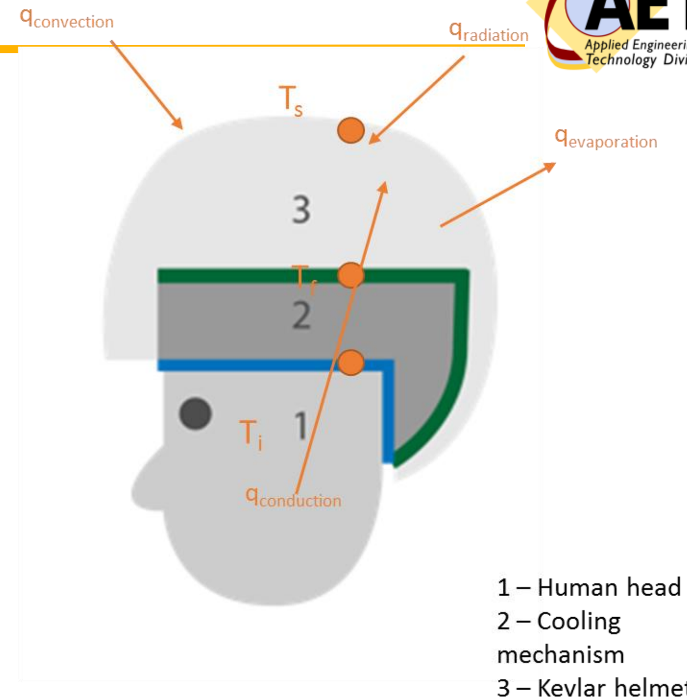
Requirements levied on the design of the helmet heat exchanger.

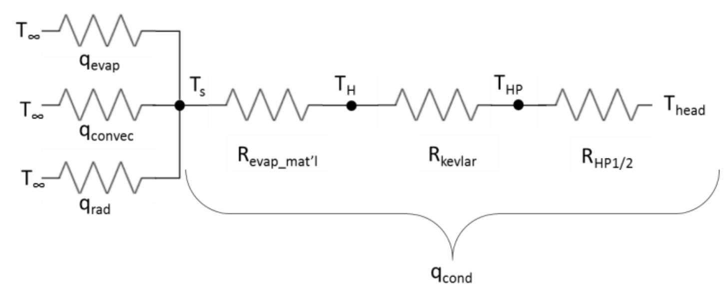
This work is focusing on the thermal requirements. Other TBDs will be removed at a later date once design verification has occurred.

	Human Variability
	Thermal
	Structural (Material)
	Power
	Systems (Interfaces)

Proof-of-concept model

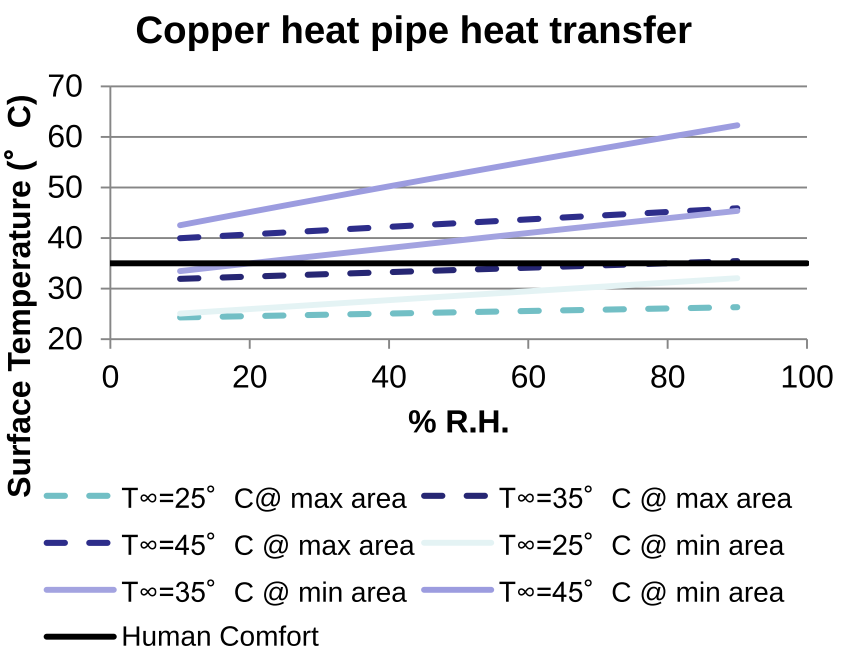
- Excel Newton-Raphson root finding method to solve for a transcendental, non-linear energy balance
- Assumptions:
  - Steady-state conditions
  - Dry air behaves as an ideal gas
  - Constant properties, except for variable specific volume in temperature range of interest
  - For the radiation exchange calculations, the wicking material surface is small in comparison to the large, isothermal surroundings
  - No heat loss/gain occurs from any surface other than external helmet; all other surfaces are considered adiabatic.
  - Internal convection can be neglected
  - Contact resistance between wicking and cooling surface is included in the resistance of the wet cloth (wicking material).





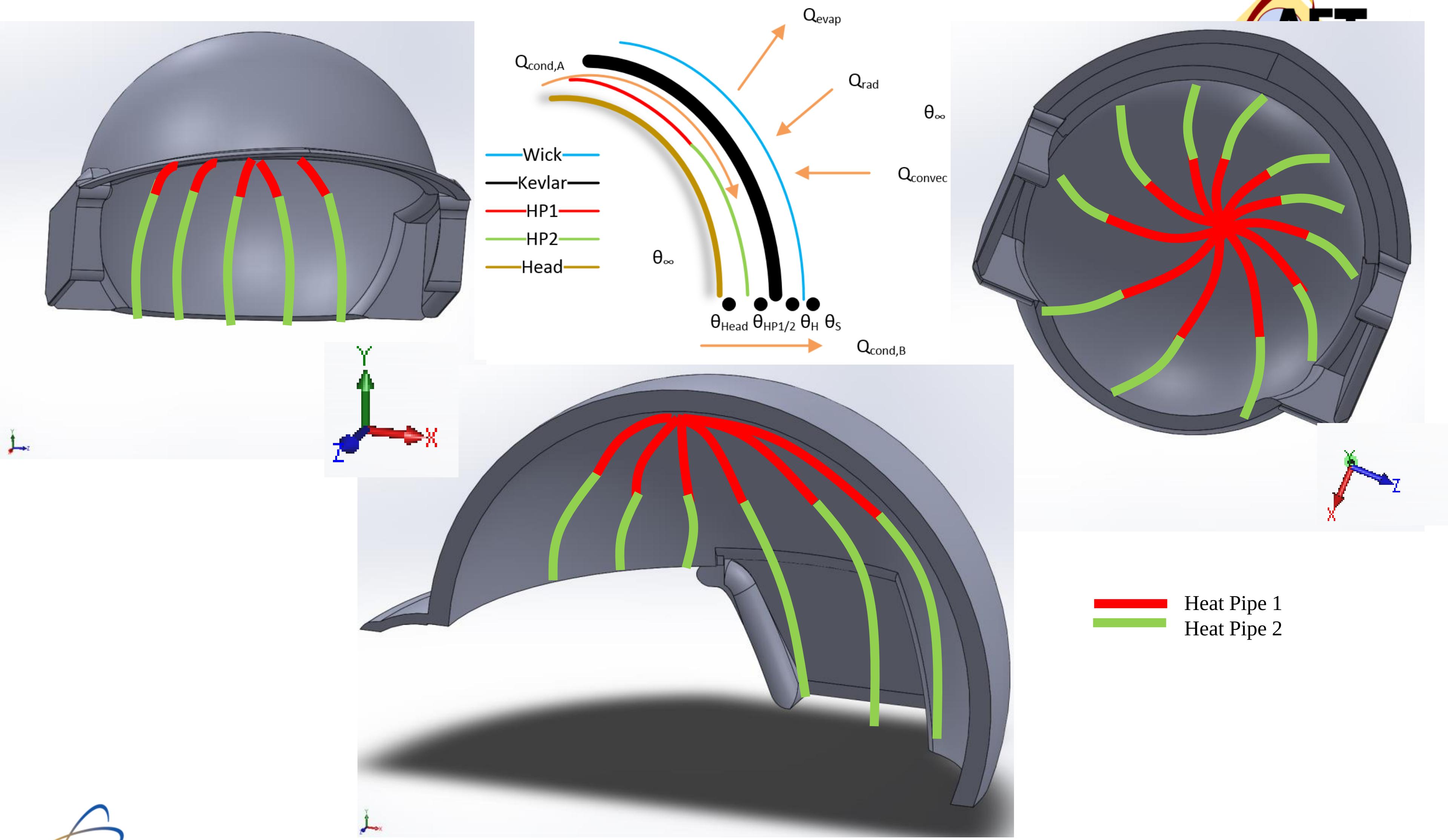
Newton-Raphson model

- Need to maximize heat transfer area internally
  - Minimum area negatively impacts performance
    - ⅓ area needs reconsideration
- Evaporative cooling saturates at temperatures above ~28° C
- Need to have more accurate model without all these assumptions



Conceptual Design Phase – Initial Designs

HELMET HEAT EXCHANGER



$Q_{cond,A}$
Q_{evap}
Q_{rad}
θ_∞
Q_{convec}
Wick
Kevlar
HP1
HP2
Head
θ_∞
θ_{Head} $\theta_{HP1/2}$ θ_H θ_S
$Q_{cond,B}$
Heat Pipe 1
Heat Pipe 2

Generic model before HP selection – slide 1

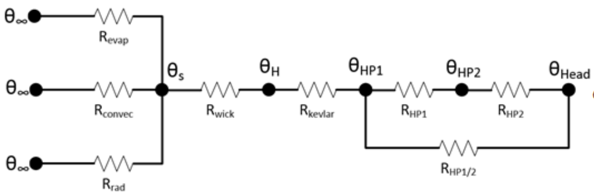
Helmet Heat Exchanger Sensitivity Analyses

Problem Definition

In order to cool a Kevlar millitary helment,it is proposed to use a internal heat exchanger. The heat exchanger will line the internal surface of the helment and will consist of heat pipes connected to a wicking material lining the external surfces of the helmet, inducing passive evaporation. There are several mechanisms of cooling in the system and the schematics of the system are included below.

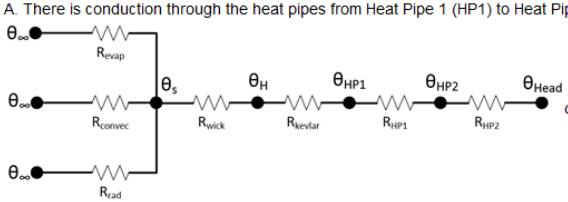
1. Conduction: Internal conduction

The total conduction is given by the following resisticve schematic where the heat pipe resistors are tuneable:



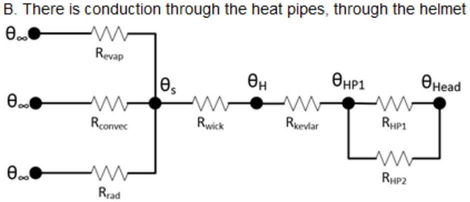
$$q_{cond} = \frac{\theta_S - \theta_H}{R_{wick}} + \frac{\theta_H - \theta_{HP1}}{R_{kevlar}} + \left(\frac{\theta_{HP1} - \theta_{HP2}}{R_{HP1}} + \frac{\theta_{HP2} - \theta_{Head}}{R_{HP2}}\right) // \frac{\theta_{HP1/2} - \theta_{Head}}{R_{HP1//2}}$$

A. There is conduction through the heat pipes from Heat Pipe 1 (HP1) to Heat Pipe 2 (HP2). - Along the x-axis.



$$q_{cond,A} = \frac{\theta_S - \theta_H}{R_{wick}} + \frac{\theta_H - \theta_{HP1}}{R_{kevlar}} + \frac{\theta_{HP1} - \theta_{HP2}}{R_{HP1}} + \frac{\theta_{HP2} - \theta_{Head}}{R_{HP2}}$$

B. There is conduction through the heat pipes, through the helmet and the wicking material. - Along the y-axis.



$$q_{cond,B} = \frac{\theta_S - \theta_H}{R_{wick}} + \frac{\theta_H - \theta_{HP1/2}}{R_{kevlar}} + \frac{\theta_{HP1/2} - \theta_{Head}}{R_{HP1//2}}$$

2. Convection: external around the helmet: $q_{convec} = h_{convec}(\theta_\infty - \theta_s)$
3. Radiation: external radiation from the surface of the wicking material: $q_{rad} = \sigma\, \epsilon_{wick}\left(\theta_\infty^4 - \theta_s^4\right)$
4. Evaporation: external evaporation from the surface of the wicking material: $q_{evap} = h_m\, h_{fg,water,s}(\rho_{vator,s} - \phi_\infty\, \rho_{\infty,s})$

Thus, the energy balance becomes: $q_{cond} + q_{rad} + q_{convec} + q_{gain} = q_{evap} + q_{loss}$

Note the heat transfer (laterally, z-axis) from one heat pipe set to the next heat pipe set has been neglected. As this was assumed to be negligible.

Model assumes that the θ_{head} = 290 [C], thermal comfort zone for humans, and solves for the θ_s, surface temperature of the helmet at the boundary of the wicking material

Generic model before HP selection – slide 2

Assumptions

1. Steady - state conditions apply
2. Uniform assumed radiation exchange with the surroundings = 0.92
3. Uniform convective heat transfer coefficient via both natural & forced convection
4. The loss is set to 0.0 W = q_{loss}
5. Material: The heat pipes are constructed from copper (bronze)

Model developed in Engineering Equation Solver

Note: The length of the heat rods will vary depending on location in the helmet. This study was to determine the material properties capable of moving the heat through the helmet. Therefore the calculation took the HP as running from the front to the back of the helmet, and did not use the lengths of the ordered HPs.

```
"Constants - Engineering/knowns"
g = 9.81 ;"Gravity - [m/s^2] "
Sigma = 5.67E-8; " Stefan-Boltzmann constant - [W/m^2K^4] "
k_wick = 0.03; "Wicking material thermal conductivity, assumed felt - [W/m K] "
k_kevlar = 0.04; "Kevlar thermal conductivity - [W/m K] "
k_bronze =   52; "Commercial copper thermal conductivity - [W/m K] "
k_polymer =   0.2; "Commercial copper thermal conductivity - [W/m K] "

"Air Thermodynamic Constants"
k_air_infinity=conductivity(Air,T=Theta_infinity)  "Thermal conductivity of air - [W/m K]"
alpha_air_infinity=k_air_infinity/(rho_air_infinity*cp_air_infinity) "Thermal diffusivity -  [m^2/s]"
mu_air_infinity=viscosity(Air,T=Theta_infinity) "Dynamic viscosity of air - [N s/m^2] "
nu_air_infinity=mu_air_infinity/rho_air_infinity "Kinematic viscosity of air - [m^2/s]"
beta_air=volexpcoef(Air,T=Theta_infinity) "Thermal coefficient -based off T_infinity"
D_water_air=0.26E-4 "Binary diffusion coefficient for water/air - [m/s]"
rho_air_infinity=density(Air, T=Theta_infinity,P=P_infinity) "Air density at T_infinity -  [kg/m^3]"
cp_air_infinity=cp(Air,T=Theta_infinity)  "Specific Heat of Air at T_infinity - [J/kg K]"

"Water Thermodynamic Constants"
h_fg_water_s=2438E3 [J/kg] "Enthalpy of two-phase water"
v_g_water_s=25.2158 [m^3/kg] "Water specific volume at surface temperature"
rho_water_s=1/v_g_water_s  "Water density at T_s - [kg/m^3]"
rho_water_infinity=1/v_g_water_infinity  "Water density at T_infinity - [kg/m^3]"

"VARIABLES TO CHANGE"
v_g_water_infinity=15.26[m^3/kg] "Saturated specifiv volume of ambient conditions"   "<------------
Phi_assumed = 0.3; "Relative humidity - [%] "
Epsilon_wick = 0.95;"Wicking material emissivity - [-] "
Theta_0 = 290 ; "Intial internal head temperature - [K] "

"Constants - set per our discression"
P_Infinity = 101.325 ;"Standard atmospheric pressure - [kPa] "
Theta_Infinity = 318; "Ambient environmental temperature - [K] "
u_air = 0.15; "Velocity of air - [m/s] "
```

Dimension definitions and calculations

$D_{h,ext} = 0.7366$ Diameter of helmet wrapped around largest part - [m]

$A_{h,ext} = 2 \cdot \pi \cdot \left[\frac{D_{h,ext}}{2}\right]^2$ "Exterior area for evaporation - [(m^2)]

$D_{h,int} = D_{h,ext} - 2 \cdot t_h$ Diameter of helmet wrapped around largest part - [m]

$A_{h,int} = 2 \cdot \pi \cdot \frac{\left[\frac{D_{h,int}}{2}\right]^2}{3}$ $\boxed{\text{Interior area for heat pipes, assumes only 1/3 interior area - [(m}^2\text{)]}}$

$W_{h,e} = 0.508$ "Exterior ar to ear length - [m]

$L_{h,f} = 0.4318$ "Exterior forehead to neck length - [m]

$t_{kevlar} = 0.0127$ "Kevlar thickness - [m]

$\frac{t_{HP1}}{2} = 0.012$ Heat pipe thickness - [m]

$t_{wick} = 0.006$ Wicking material thickness - [(m^2)]

$t_h = 0.012$ "Helment thickness - [m

Generic model before HP selection – slide 3

Thermal Resistance calculations

$$R_{wick} = \frac{t_{wick}}{k_{wick}}$$ "Wicking material thermal resistance - [m² K/W]

$$R_{kevlar} = \frac{t_{kevlar}}{k_{kevlar}}$$ "Kevlar thermal resistance - [m² K/W]

$$R_{HP1} = \frac{t_{HP1}}{2 \cdot k_{bronze}}$$ "HP1 (assumed bronze) thermal resistance - [m² K/W]

$$R_{HP2} = \frac{t_{HP1}}{2 \cdot k_{bronze}}$$ HP2 (assumed bronze) thermal resistance - [m² K/W]

$$R_{HP,ser} = R_{HP1} + R_{HP2}$$ Thermal reistance of HP1 and 2 in series, method A - [m² K/W]

$$R_{HP,par} = \frac{R_{HP1} \cdot R_{HP2}}{R_{HP1} + R_{HP2}}$$ HP1//2 parallel resistance - for conduction B - [m² K/W]

$$R_{HP,total} = \frac{R_{HP,ser} \cdot R_{HP,par}}{R_{HP,ser} + R_{HP,par}}$$ Total heat pipe thermal resistance for both series/parallel pipes - [m² K/W]

$$R_{total} = R_{wick} + R_{kevlar} + R_{HP,total}$$ Total resistance - with the heat pipes - [m² K/W]

"Thermal Equation

$$q_{cond} = \frac{\theta_{head} - \theta_s}{R_{total}}$$

$$q_{conv} = h_{conv} \cdot (\theta_\infty - \theta_s)$$

$$q_{rad} = \sigma \cdot \varepsilon_{wick} \cdot (\theta_\infty^4 - \theta_s^4)$$

$$q_{evap} = h_m \cdot h_{fg,water,s} \cdot (\rho_{water,s} - \phi_{assumed} \cdot \rho_{water,\infty})$$

$$q_{cond} + q_{rad} + q_{conv} = q_{evap}$$

$$\theta_{head} = \theta_0$$

Convection Calculations

$$Re_{rect} = \frac{\rho_{air,\infty} \cdot u_{air} \cdot D_{h,ext}}{\mu_{air,\infty}}$$ Reynolds number - laminar flow

$$Ra_{free} = Gr_{conv} \cdot Pr_{conv}$$ Rayleigh number - free convection

$$Pr_{conv} = \frac{cp_{air,\infty} \cdot \mu_{air,\infty}}{k_{air,\infty}}$$ Prandtl number - forced convection

$$Gr_{conv} = \left| \frac{g \cdot \beta_{air} \cdot (\theta_0 - \theta_\infty) \cdot L_{h,f}^3}{\nu_{air,\infty}^2} \right|$$

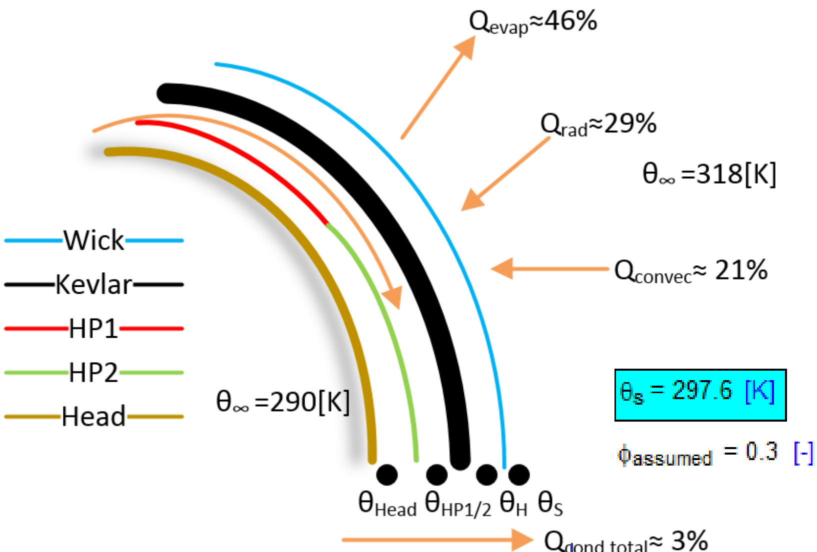
$$Le_{conv} = \frac{\alpha_{air,\infty}}{D_{water,air}}$$ Lewis number [-]

$$\nu_{total} = \left[0.825 + \frac{0.387 \cdot Ra_{free}^{(1/6)}}{\left(1 + \left[\frac{0.492}{Pr_{conv}}\right]^{\left[\frac{9}{16}\right]}\right)^{\left(\frac{8}{27}\right)}} \right]^2$$ Total Nusselt number - [W/m K]

$$h_{conv} = \frac{k_{air,\infty} \cdot \nu_{total}}{L_{h,f}}$$ Convective heat transfer coefficient - [W/m² K]

$$h_m = \frac{h_{conv}}{\rho_{air,\infty} \cdot cp_{air,\infty} \cdot Le_{conv}^{(2/3)}}$$ Mass transfer coefficient - [-]

Generic model before HP selection – slide 4

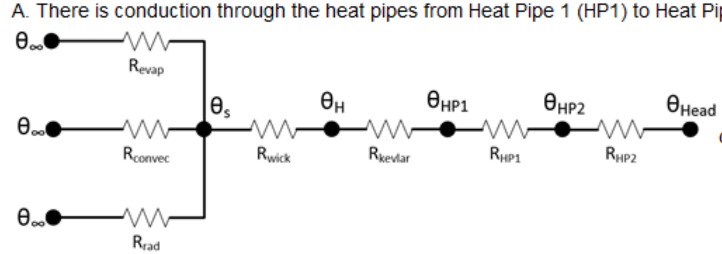


Setting the maximum internal head temperature to 290 K, and solving for the surface temperature we get the heat transfer mechanisms.

Note: that the conduction of the heat pipes was done with bronze only, and did not include the polymer material as we had not determined how the 3D printing would play a role in the design.

~80 %

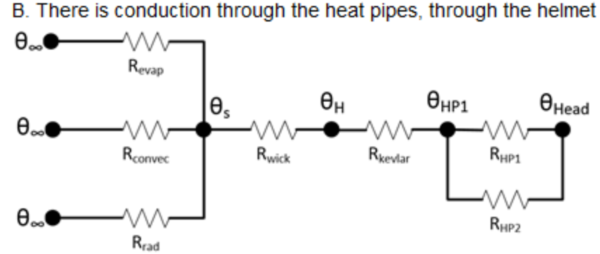
A. There is conduction through the heat pipes from Heat Pipe 1 (HP1) to Heat Pipe 2 (HP2). - Along the x-axis.



$$q_{cond,A} = \frac{\theta_S-\theta_H}{R_{wick}} + \frac{\theta_H-\theta_{HP1}}{R_{kevlar}} + \frac{\theta_{HP1}-\theta_{HP2}}{R_{HP1}} + \frac{\theta_{HP2}-\theta_{Head}}{R_{HP2}}$$

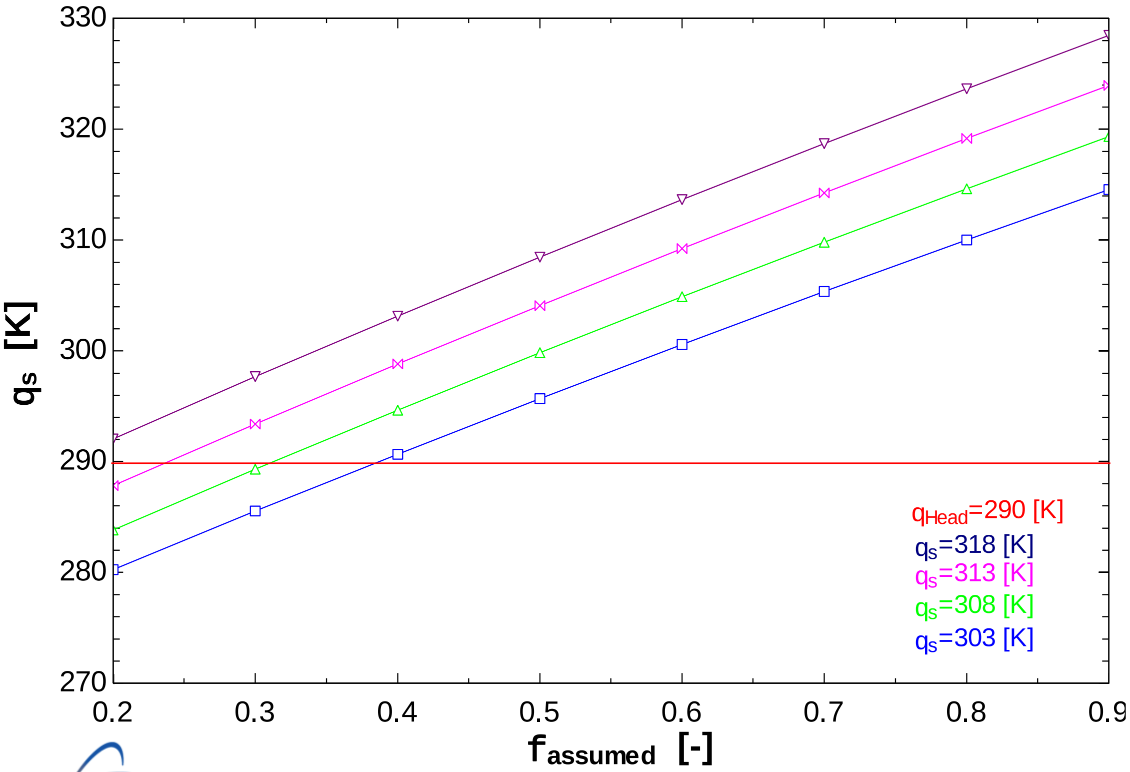
~20 %

B. There is conduction through the heat pipes, through the helmet and the wicking material. - Along the y-axis.



$$q_{cond,B} = \frac{\theta_S-\theta_H}{R_{wick}} + \frac{\theta_H-\theta_{HP1/2}}{R_{kevlar}} + \frac{\theta_{HP1/2}-\theta_{Head}}{R_{HP1//2}}$$

EES Numerical Results

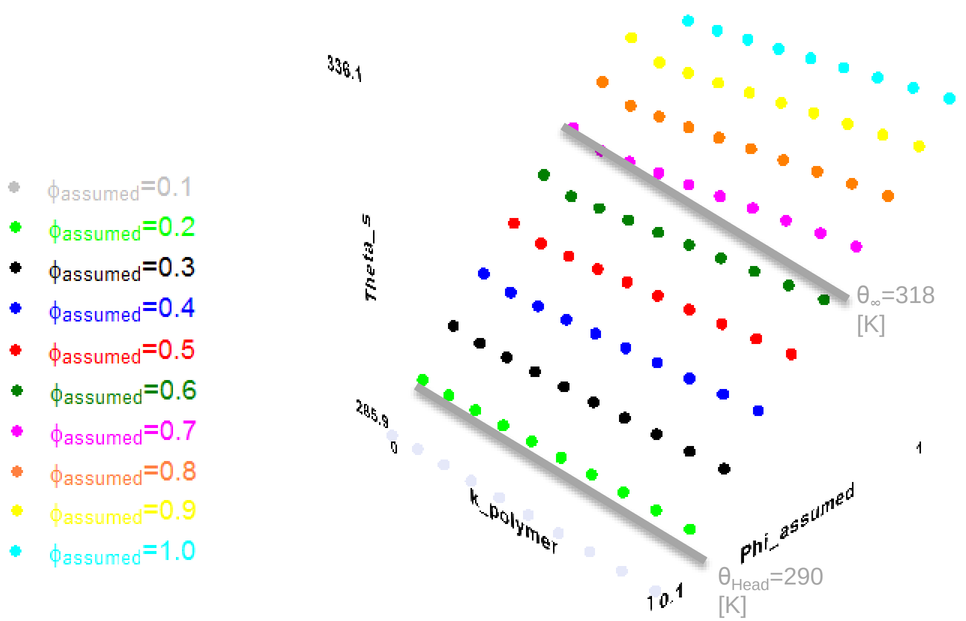


The current model assumes that the internal temperature of the helmet is set at θ_{Head}=290 [K], the human comfort threshold.

- The helmet heat exchanger will have only a small window of operations to reach the target performance:
  - % R.H. < ~28%
  - T_{∞} < ~308[K] (35° C)

Sensitivity Analysis – Thermal Conductivity 1

x-axis: $0 < k_{polymer} < 1$ [W/K-m]
y-axis: $0.1 < \phi_{assumed} < 1$ [-]
z-axis: $285.9 < \theta_s < 336.1$ [W/K-m]

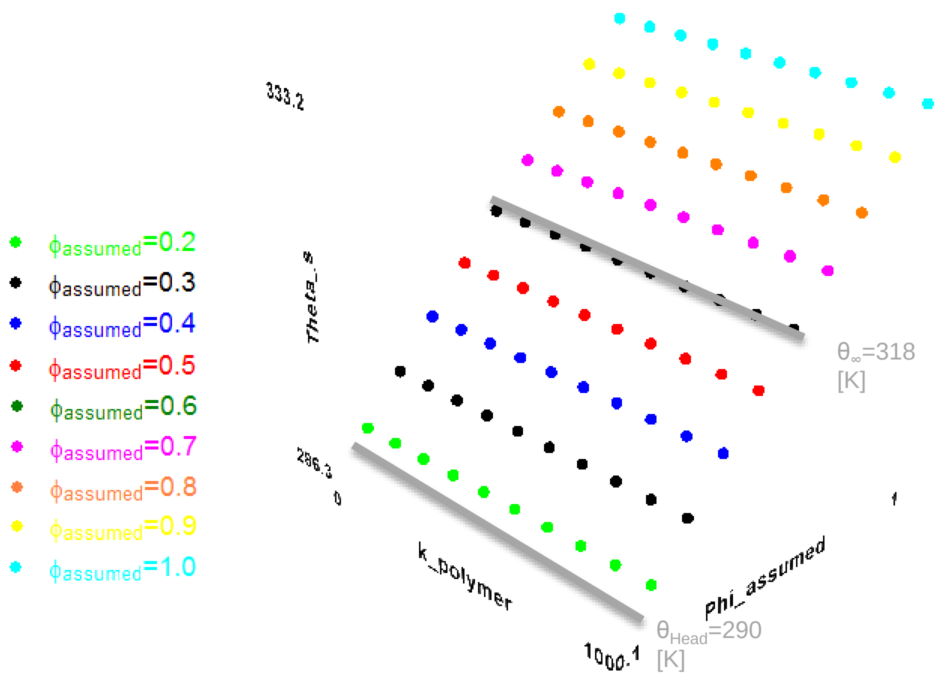


The current model assumes that the internal temperature of the helmet is set at $\theta_{Head}=290$ [K], the human comfort threshold. Note $\theta_{\infty}=318$ [K].

- Using the thermal resistive circuit shown previously, this means the thermal conductivity change was too small to see measurable results
  - The ambient R.H. has a higher impact on results than the thermal conductivities.
    - The helmet will not work for RH > 0.2 to keep head
  - Note that the thermal conductivity values of k < 1[W/m K] are reminiscent of polymers

Sensitivity Analysis – Thermal Conductivity 2

x-axis: $1 < k_{polymer} < 100$
y-axis: $0.1 < \phi_{assumed} < 1$
z-axis: $286.3 < \theta_s < 333.2$



The current model assumes that the internal temperature of the helmet is set at θ_{Head}=290 [K], the human comfort threshold. Note θ_∞=318 [K].

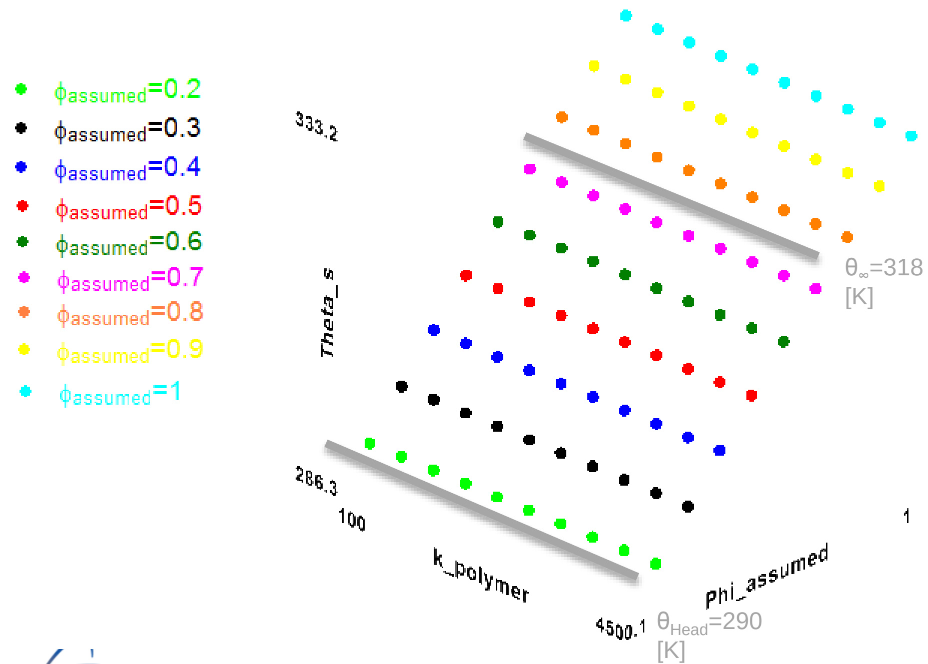
- Using a higher thermal conductivity value for the heat pipes provides minimal changes to the surface temperature:

K value [W/m-K]	Min θ_s [K]	Max θ_s [K]	Δ [K]
0.1< k <1	285.9	336.1	2.9
1 < k <100	286.3	333.2	

- The ambient R.H. has a higher impact on results than the thermal conductivities.
- Note that the thermal conductivity values of k < 1[W/m K] are NOT reminiscent of polymers, but closer to metals

Sensitivity Analysis – Thermal Conductivity 3

x-axis: 100 < $k_{polymer}$ < 450
y-axis: 0.1 < $\phi_{assumed}$ < 1
z-axis: 286.3 < θ_s < 333.2



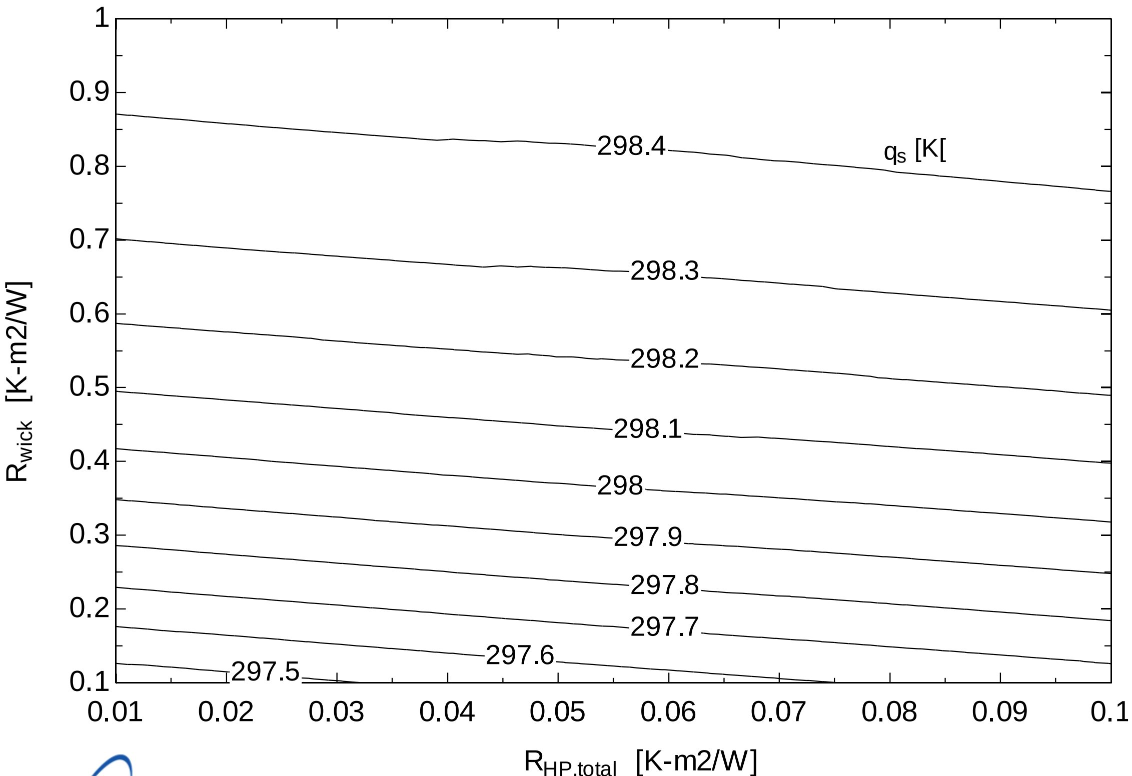
The current model assumes that the internal temperature of the helmet is set at θ_{Head}=290 [K], the human comfort threshold. Note θ_{∞}=318 [K].

- Using a higher thermal conductivity value for the heat pipes provides minimal changes to the surface temperature.

K value [W/m-K]	Min θ_s [K]	Max θ_s [K]	Δ [K]
0.1< k <1	285.9	336.1	2.9
1 < k <100	286.3	333.2	
100 < k < 450	286.3	333.2	0

- The thermal conductivity of the heat pipes is not a significant contributor to the heat transfer process of the system
  - We can choose material as we see fit for our applications

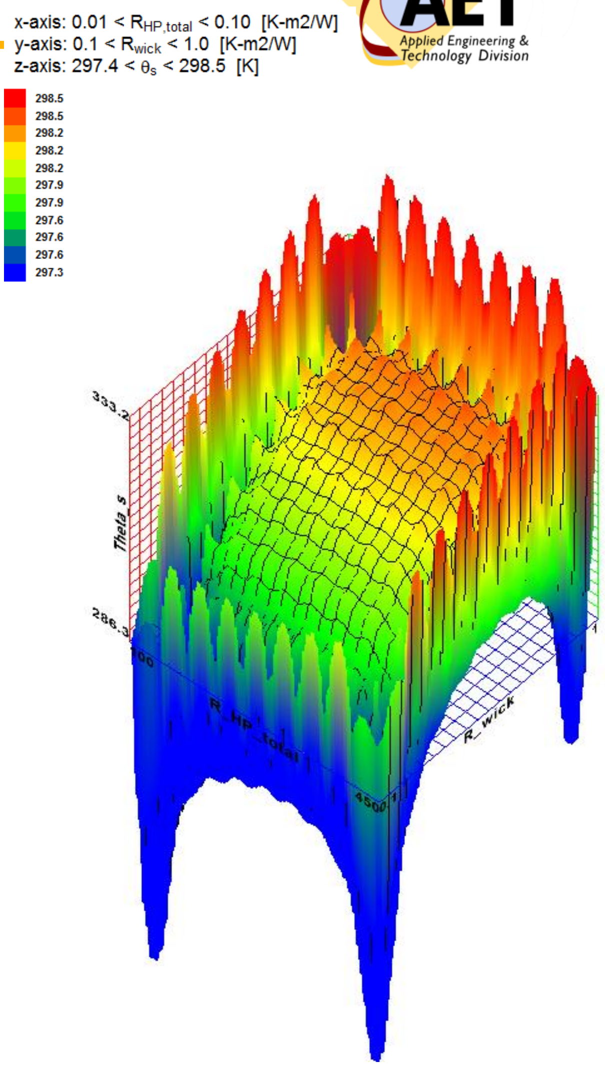
Sensitivity Analysis – R values 1

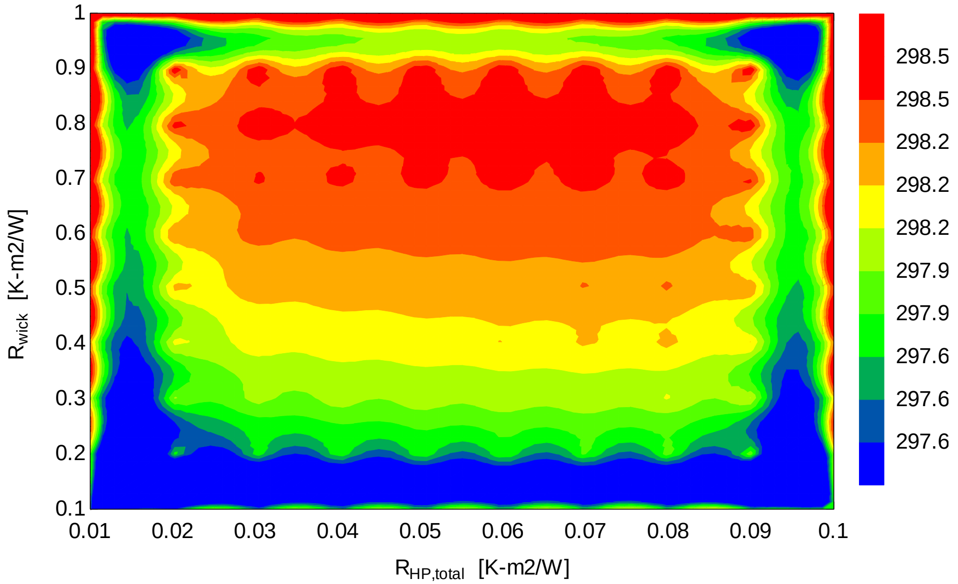


- The greatest contributor to the thermal performance through the helmet is the R_{wick} and R_{kevlar} based upon material thickness
  - Altering the $R_{HP1,2}$ don't play that large of a role in the final θ_s
  - For example, at θ_∞=318 [K], and R.H.=0.3, the R values are:

	% Total
$R_{HP,total}$ = 0.00009231 [K-m2/W]	<1%
R_{kevlar} = 0.3175 [K-m2/W]	~61%
R_{wick} = 0.2 [K-m2/W]	~38%
R_{total} = 0.5176 [K-m2/W]	

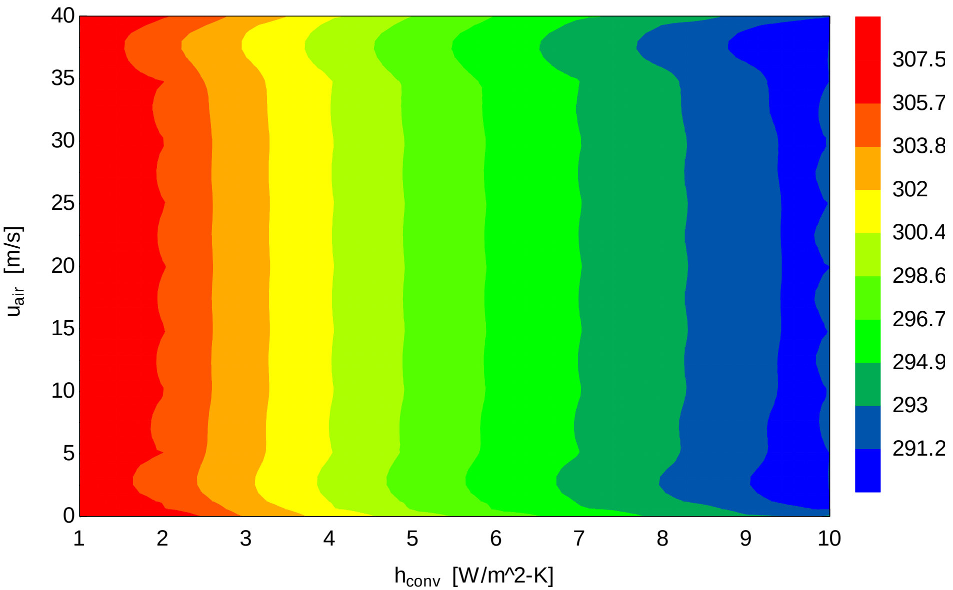
Sensitivity Analysis – R values 2



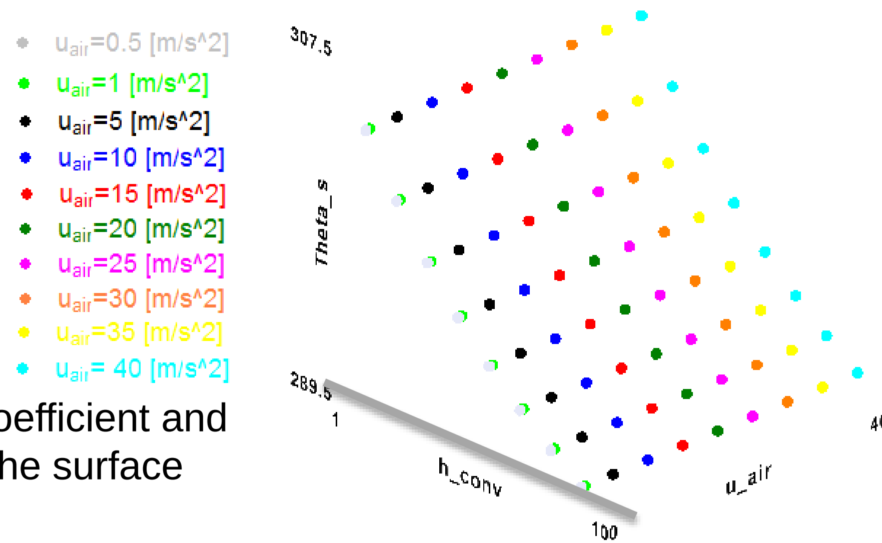


Again, there is not much of a contribution to the heat transfer of the overall system from varying the heat pipes. Our best efforts might be to consider a different helmet material.

Sensitivity Analysis – h_{conv} and u_{air}



x-axis: 1.0 < h_{conv} < 10.0 [W/m^2-K]
y-axis: 0 < u_{air} < 40 [m/s]
z-axis: 289.5 < θ_s < 307.5 [K]



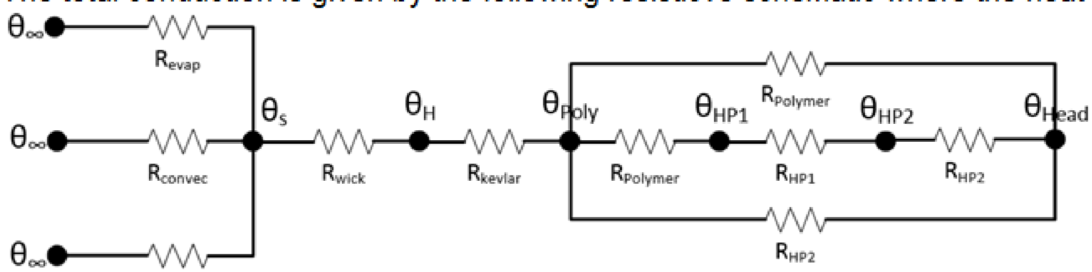
θ_{Head}=290 [K]

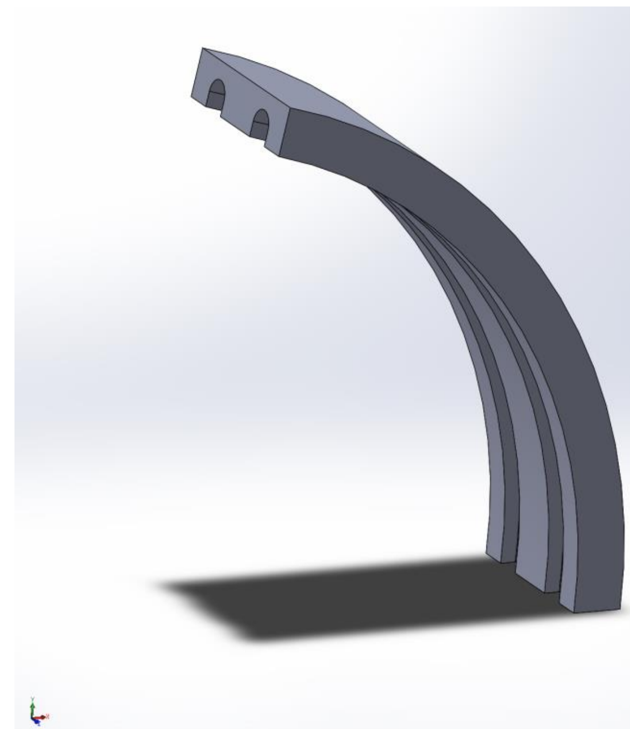
- Assuming θ_∞=318 [K], the convective heat transfer coefficient and air flow velocity were varied to determine effects on the surface temperature, θ_s.
  - The target surface temperature is only met at higher convective heat transfer values (h_{conv}>8 [W/m^2-K]), regardless of all air flow velocities
  - Air flow velocities aid in cooling the helmet, but still don't reach the target temperature

3D printing in the system

1. Conduction: Internal conduction

The total conduction is given by the following resisticve schematic where the heat pipe resistors are tuneable:



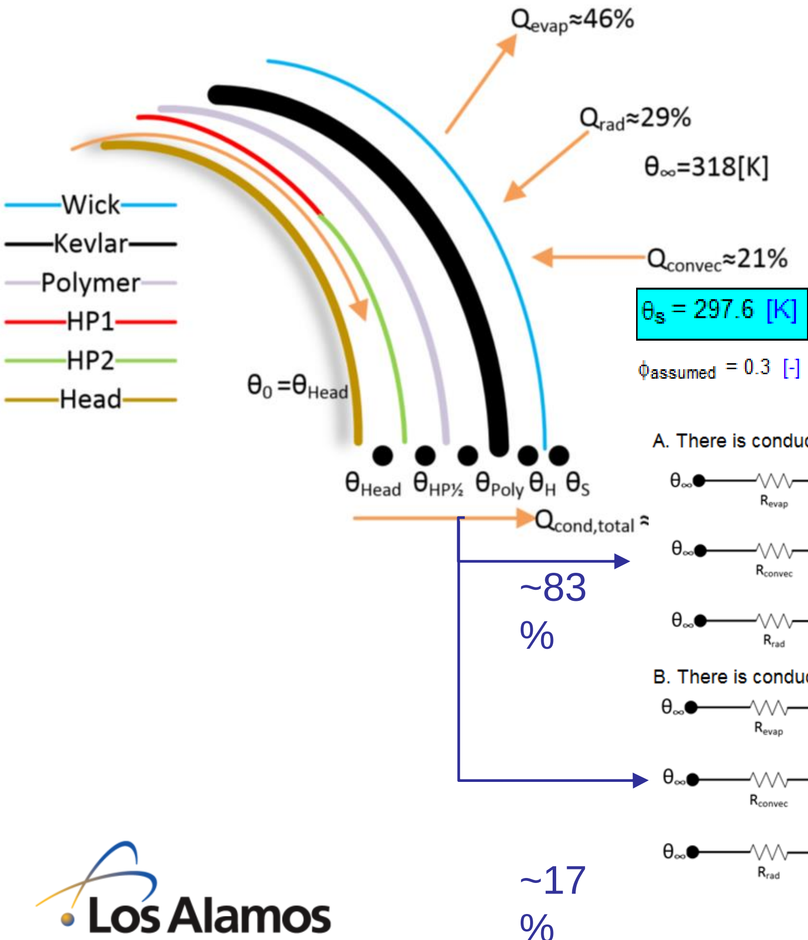


Designs for the HP holders will be the interface between the HP and the helmet, altering the conduction.

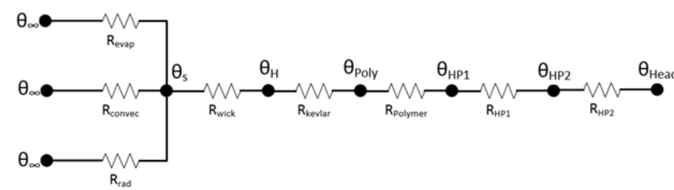
3D printing holders analysis

Setting the maximum internal head temperature to 290 K, and solving for the surface temperature we get the heat transfer mechanisms.

Using the thermal conductivity of PLA, and assuming a thickness double that of the heat pipe, more heat is funneled through the HPs and not through the entire configuration.

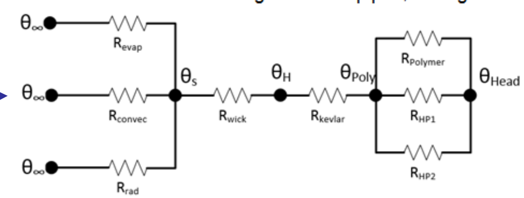


A. There is conduction through the heat pipes from Heat Pipe 1 (HP1) to Heat Pipe 2 (HP2). - Along the x-axis.



$$q_{cond,A} = \frac{\theta_S-\theta_H}{R_{wick}} + \frac{\theta_H-\theta_{Poly}}{R_{kevlar}} + \frac{\theta_{Poly}-\theta_{HP1}}{R_{Polymer}} + \frac{\theta_{HP1}-\theta_{HP2}}{R_{HP1}} + \frac{\theta_{HP2}-\theta_{Head}}{R_{HP2}}$$

B. There is conduction through the heat pipes, through the helmet and the wicking material. - Along the y-axis.



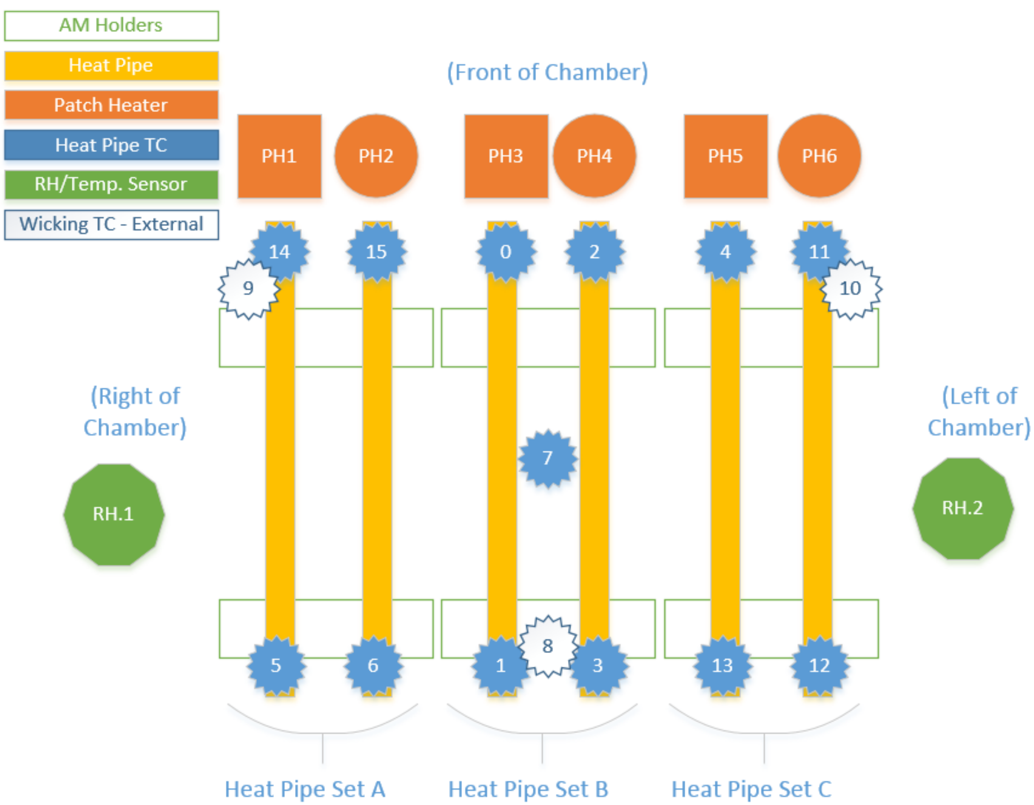
$$q_{cond,B} = \frac{\theta_S-\theta_H}{R_{wick}} + \frac{\theta_H-\theta_{HP,total}}{R_{kevlar}} + \frac{\theta_{HP,total}-\theta_{Head}}{R_{HP1//2}//R_{Polymer}}$$

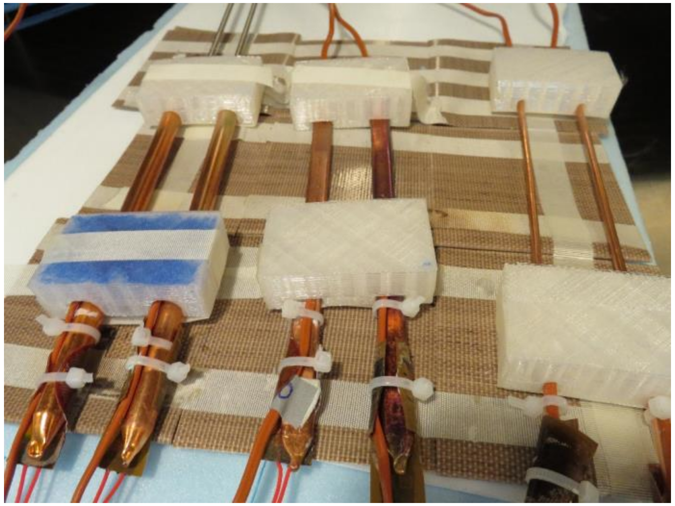
3D printing summary

- Adding in the 3D printed-holders will not significantly alter the performance of the system
  - Conduction 80% vs 83%
- Design might need some alteration
  - Need reservoir added to re-wet wick
- Using NinjaFlex as the interface in testing provides cushion to helmet/head interface

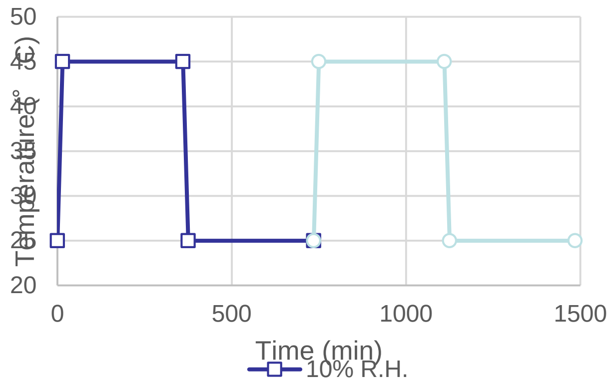
Environmental testing set-up

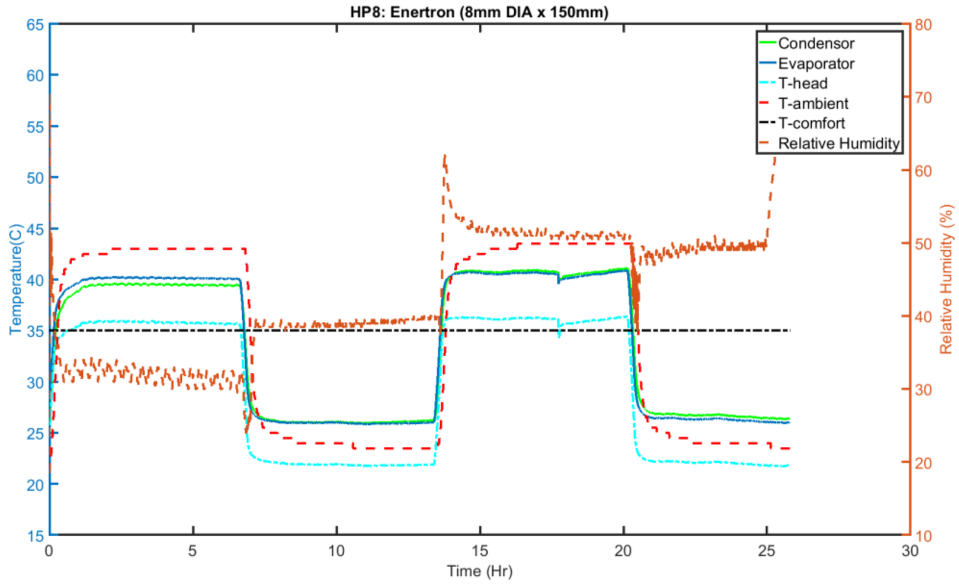
- Tested 6 sets of heat pipes with 2 sets of patch heaters
  - Square PH on odds = 70° C
  - Round PH on evens = 40° C





Experimental results – example profile





- All HPs follow the test profile, but some do it better than others
  - Initial review shows that test 1 and 2 had some differences experimentally
  - Lower temperature HP (round) do not dry out the wick as badly

Heat pipe COP

- Errors in position 5, affecting HP 5 and 11
  - Most likely wicking material contact issues
- Higher temp/Low RH has best COP
  - 7 out of 12 times
    - Poor wicking contact
    - Poor patch heater contact
    - Poor RH control
- Expected Low temp/low RH
    - 5 out of 12 times

HP1 - Enertron (8mm DIA x 200mm)

% Ambient R.H.	$T_{ambient}$ (° C)	$T_{surface}$ (° C)	T_{head} (° C)	%R.H.	COP
25.0	24.0	16.0	28.0	39	1.3
	30.0	24.7	41.9	30	1.4
50.0	24.0	22.3	30.5	50	2.7
	42.0	29.6	42.1	47	2.4

HP2 - Enertron (8mm DIA x 200mm)

% Ambient R.H.	$T_{ambient}$ (° C)	$T_{surface}$ (° C)	T_{head} (° C)	%R.H.	COP
25.0	24.0	16.0	23.4	39	2.2
	30.0	24.7	36.4	30	2.1
50.0	24.0	22.3	27.1	50	4.6
	42.0	29.6	37.7	47	3.7

HP3 - Wakefield-Vette (8.4mm flat x 200mm)

25.0	24.0	18.7	28.2	39	2.0
	30.0	30.5	41.7	30	2.7
50.0	24.0	22.3	31.7	50	2.4
	42.0	32.5	43.3	47	3.0

HP4 - Wakefield-Vette (8.4mm flat x 200mm)

25.0	24.0	18.7	27.8	39	2.1
	30.0	30.5	41.8	30	2.7
50.0	24.0	22.3	29.6	50	3.1
	42.0	32.5	42.6	47	3.2

HP5 - Thermocool (3mm DIA x 250mm)

25.0	24.0	21.4	21.5	39	275.5
	30.0	36.3	33.4	30	-12.5
50.0	24.0	22.4	26.4	50	5.6
	42.0	35.3	36.3	47	36.6

HP6 - Thermocool (3mm DIA x 250mm)

25.0	24.0	21.4	27.0	39	3.9
	30.0	36.3	40.3	30	9.0
50.0	24.0	22.4	29.1	50	3.4
	42.0	35.3	41.3	47	5.9

HP7 - Enertron (8mm DIA x 150mm)

25.0	24.0	23.1	34.8	40	2.0
	42.5	23.4	43.7	25	1.2
50.0	24.0	19.1	39.2	50	0.9
	42.0	25.5	44.3	28	1.4

HP8 - Enertron (8mm DIA x 150mm)

25.0	24.0	23.1	26.4	40	7.0
	42.5	23.4	34.5	25	2.1
50.0	24.0	19.1	29.6	50	1.8
	42.0	25.5	35.8	28	2.5

HP9 - Wakefield-Vette (8.4mm flat x 150mm)

25.0	24.0	25.1	30.0	40	5.1
	42.5	27.2	37.1	25	2.7
50.0	24.0	21.6	33.5	50	1.8
	42.0	28.9	38.4	28	3.1

HP10 - Wakefield-Vette (8.4mm flat x 150mm)

25.0	24.0	25.1	27.3	40	11.8
	42.5	27.2	34.5	25	3.7
50.0	24.0	21.6	32.4	50	2.0
	42.0	28.9	34.8	28	4.9

HP11 - Thermocool (4mm DIA x 150mm)

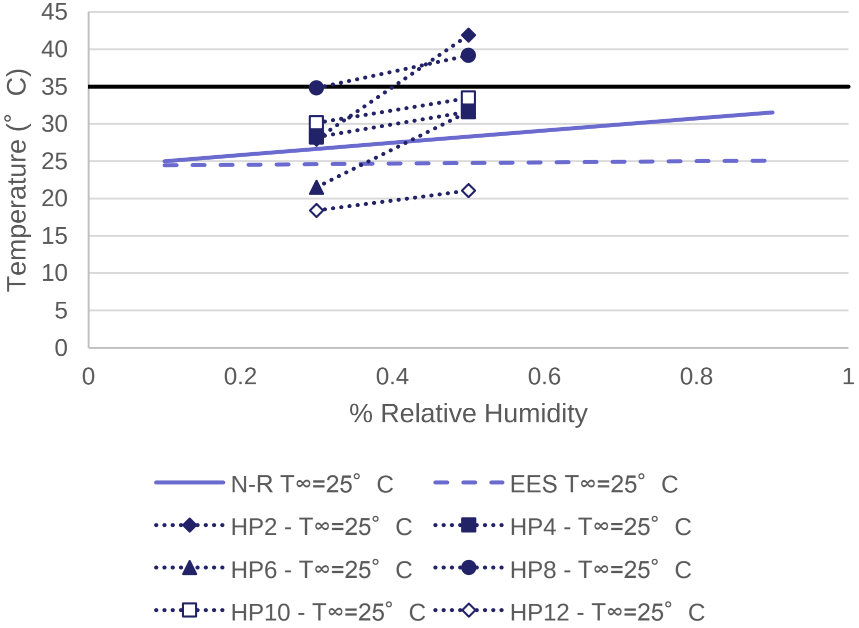
25.00	24.00	27.16	22.21	40.00	-5.48
	42.50	30.91	29.53	25.00	-22.49
50.00	24.00	24.08	24.44	50.00	67.49
	42.00	32.42	31.35	28.10	-30.36

HP12 - Thermocool (4mm DIA x 150mm)

25.0	24.00	27.16	28.56	40.00	19.42
	42.50	30.91	36.18	25.00	5.87
50.0	24.00	24.08	32.71	50.00	2.79
	42.00	32.42	36.83	28.10	7.35

Model comparisons 1

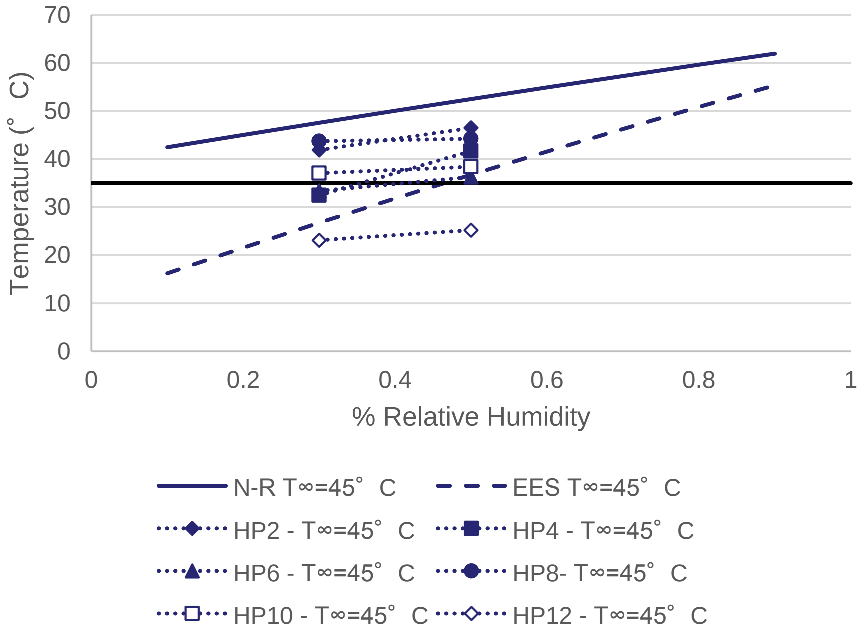
R.H. vs. T_∞=25° C, experimental and analytical



- Best HP: Thermcool 4mm DIA x 150mm
- Next best HP: Thermocool 3mm DIA x 250 mm
- Evaporative saturation <50%
- N-R & EES models undershoot performance at low temp

Model comparisons 2

R.H. vs. T_∞=45° C, experimental and analytical



- Best HP: Thermcool 4mm DIA x 150mm
- Next best HP: Thermocool 3mm DIA x 250 mm
- Evaporative saturation <40%
- N-R overshot performance
- EES undershot, then has correct rate

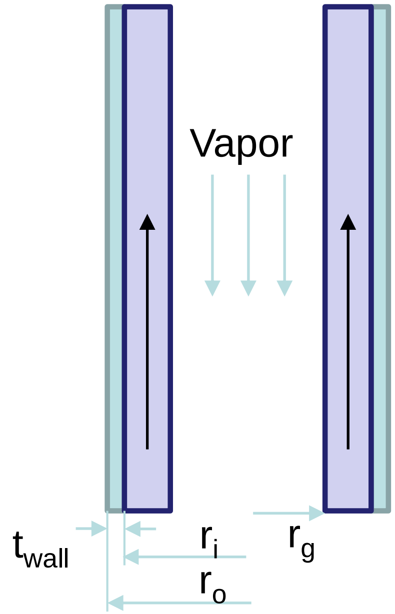
Model comparisons on the design

- Needed to characterize the heat pipes used outside system
- Holders will need revamped
  - Human comfort of fit needs to be considered
  - Helmet interface mechanism required
  - Infill, holder height and material to be reconsidered
  - Heat pipe mechanism to be defined
- Design can work up until ~45% RH and 45˚ C (amb) is optimal pipes and proper wetting
  - Smaller diameters work best, length not a huge limitation

HEAT PIPE CHARACTERIZATION

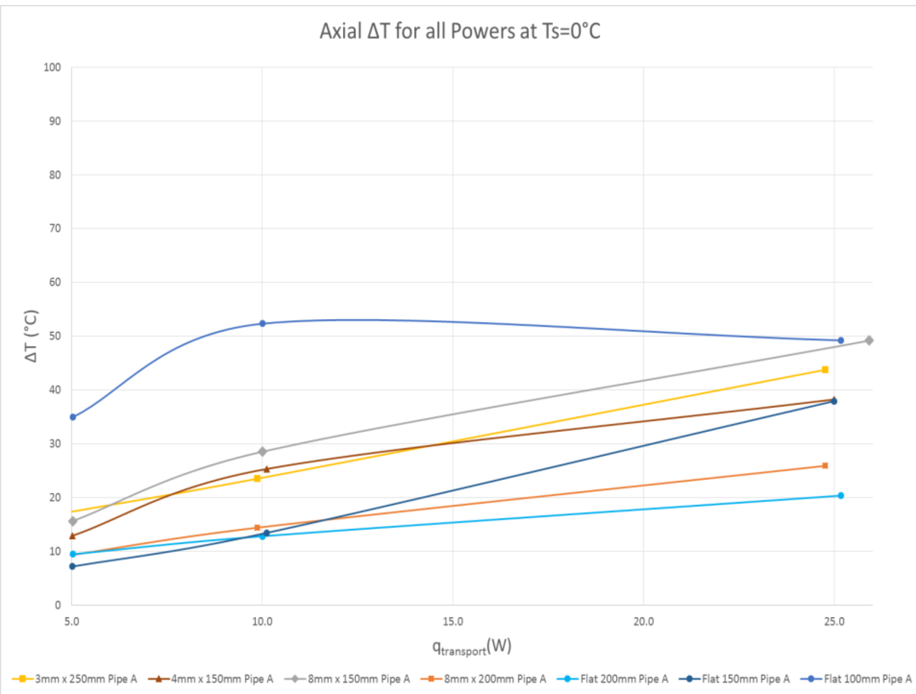
Design of Experiments

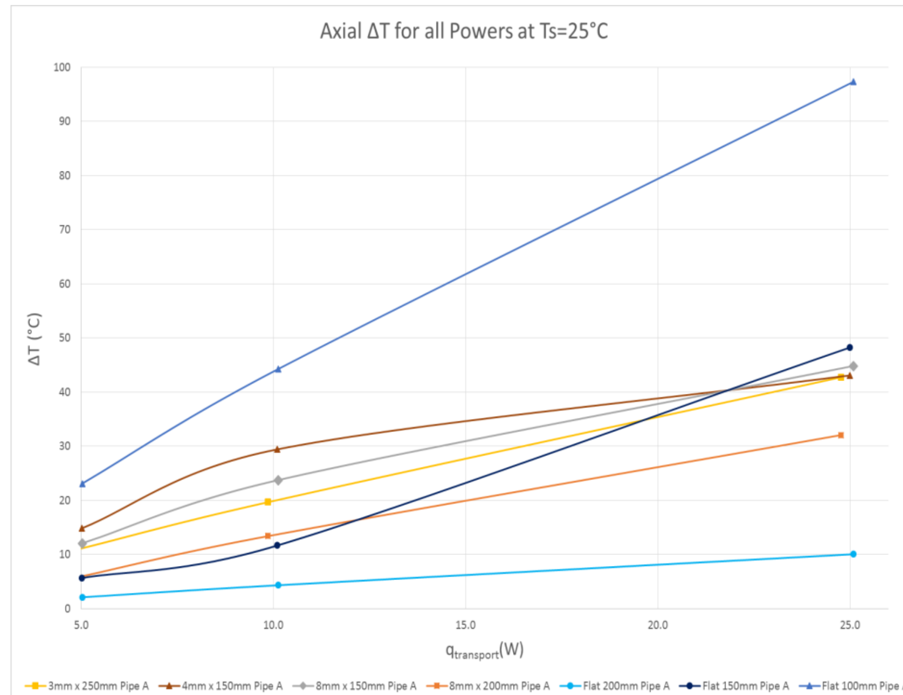
Heat Pipe Dimensions					
ID	Manufacturer	SKU	Length (mm)	Diameter (mm)	Thickness (mm)
1	Thermocool	TCHP3-9	250	3	
2	Thermocool	TCHP4-6	150	4	
3	Wakefield-Vette	120231	100	8.4	2.5
4	Wakefield-Vette	121718	200	8.4	2.5
5	Wakefield-Vette	121717	150	8.4	2.5
6	Enertron	HP-HD08DI1500BA	150	8	
7	Enertron	HP-HD08DI2100BA	200	8	



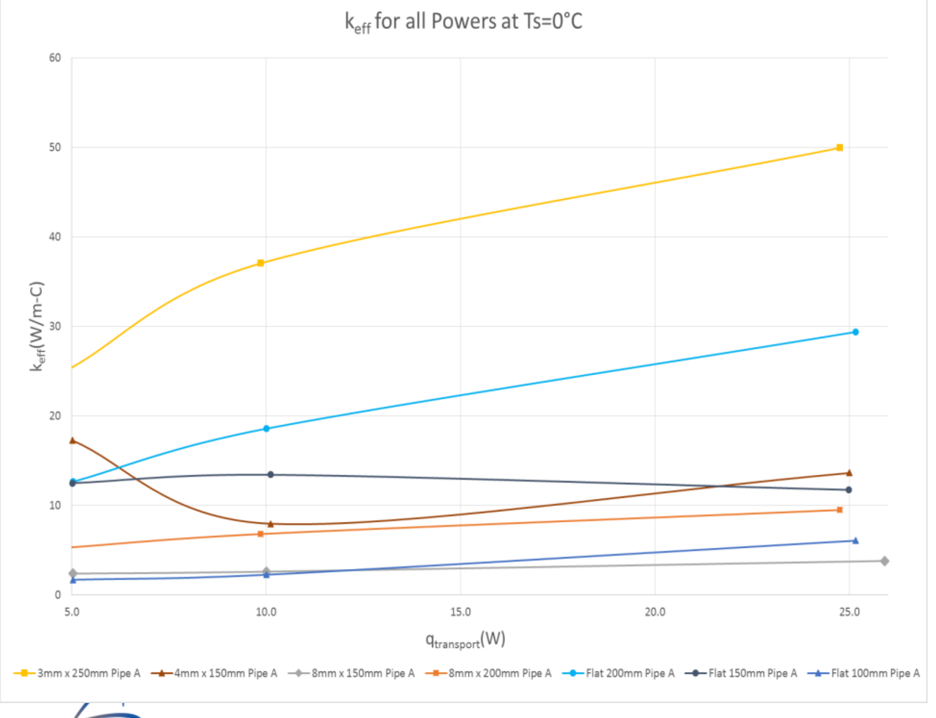
			Measured Power W)		
Test	Temp (° C)	Target Power (W)	Test 1	Test 2	Test
A	0	25	24.76	25.17	24.99
B	0	10	9.86	10.01	10.12
C	0	5	4.99	5.02	5.01
D	25	25	24.76	25.09	24.99
E	25	10	9.86	10.12	10.10
F	25	5	4.99	5.02	5.01

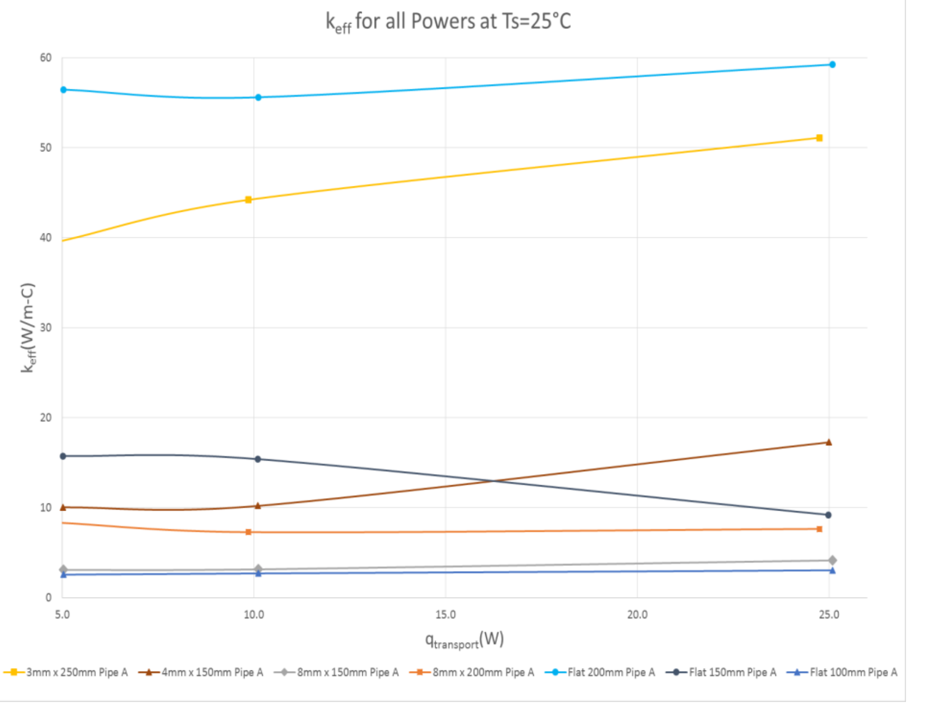
HP characterization – Axial ΔT





HP characterization – Effective Thermal Cond.

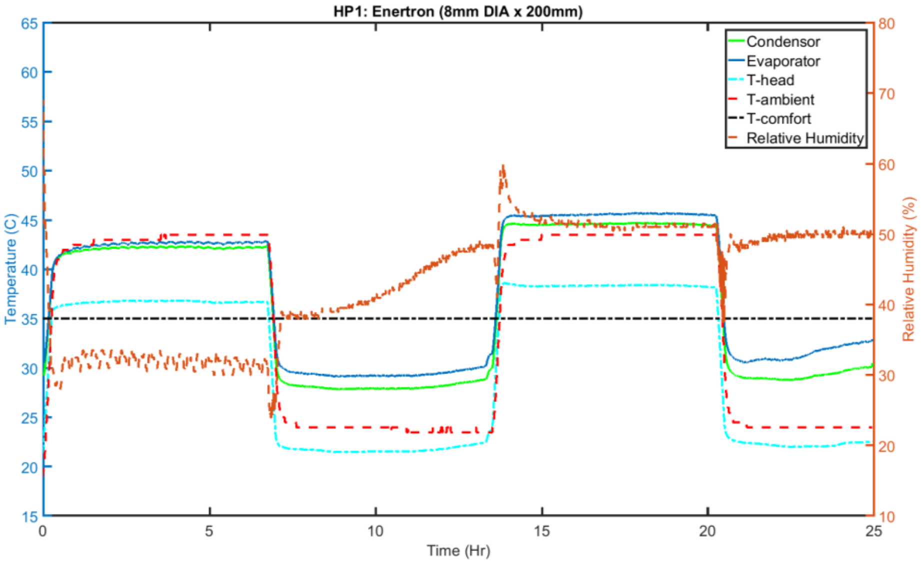


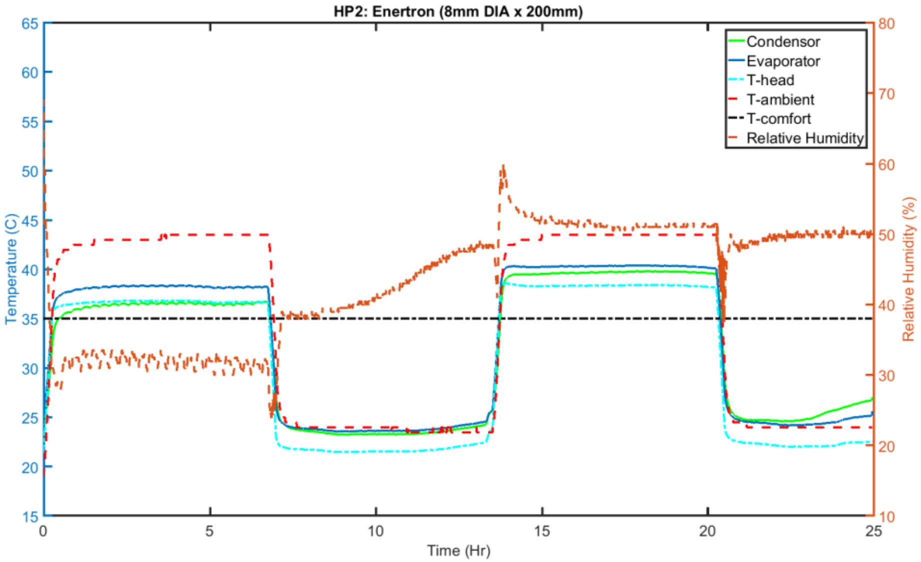


HEHV Summary + Future Work

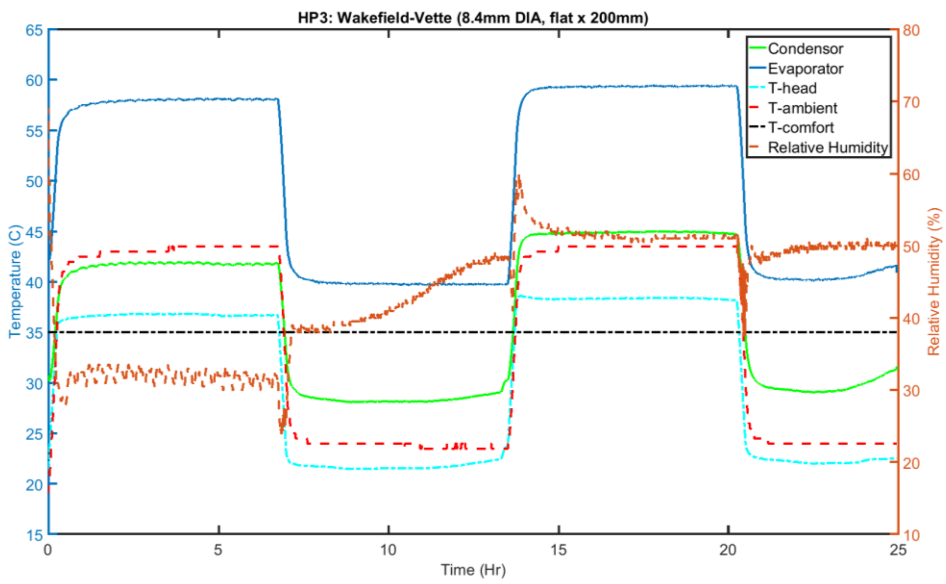
- System Design should be modified and tested with actual helmet
- Design should work, but needs:
  - Re-wetting reservoirs
  - Heat pipe selection, contingent upon actual HP characterization
    - COTS heat pipes will work fine
- Need student to continue "Phase 3" design and testing

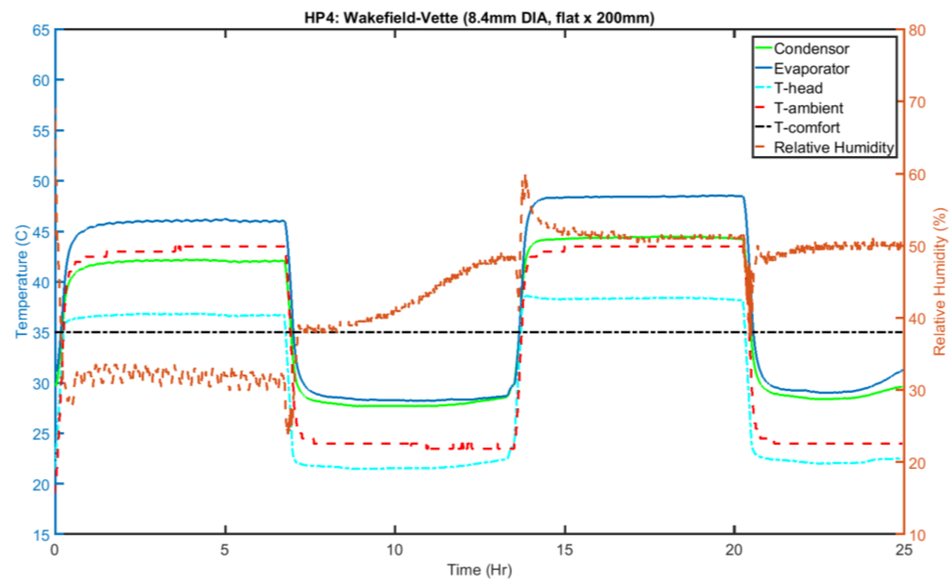
Environmental Tests per HP



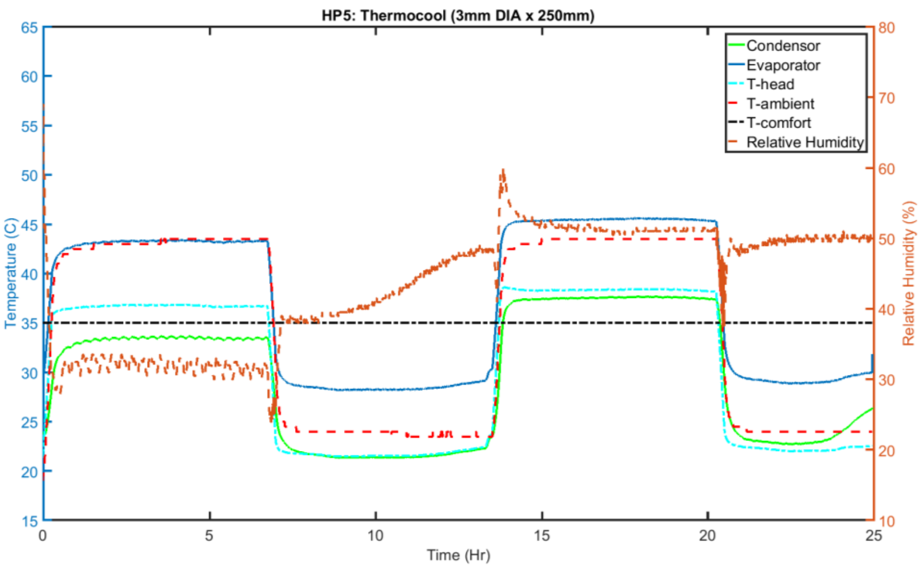


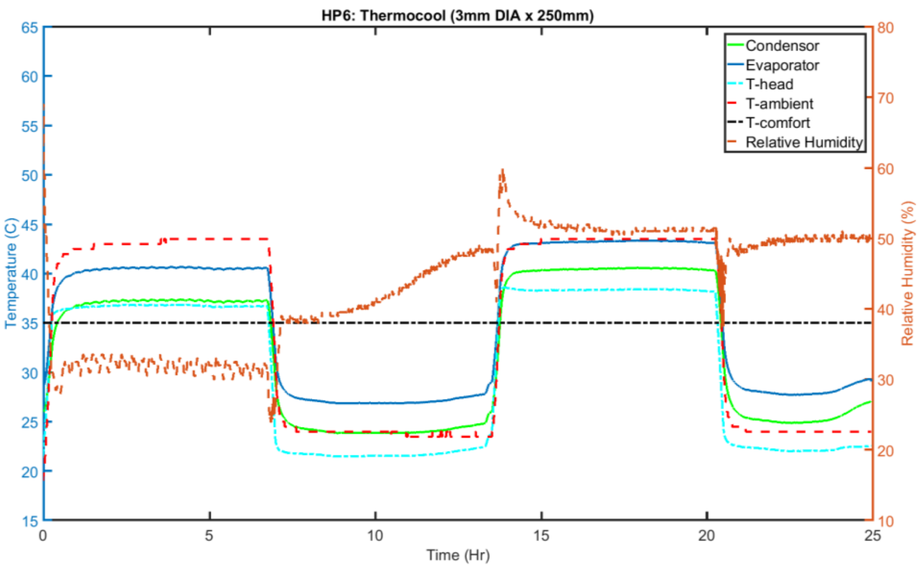
Environmental Tests per HP





Environmental Tests per HP

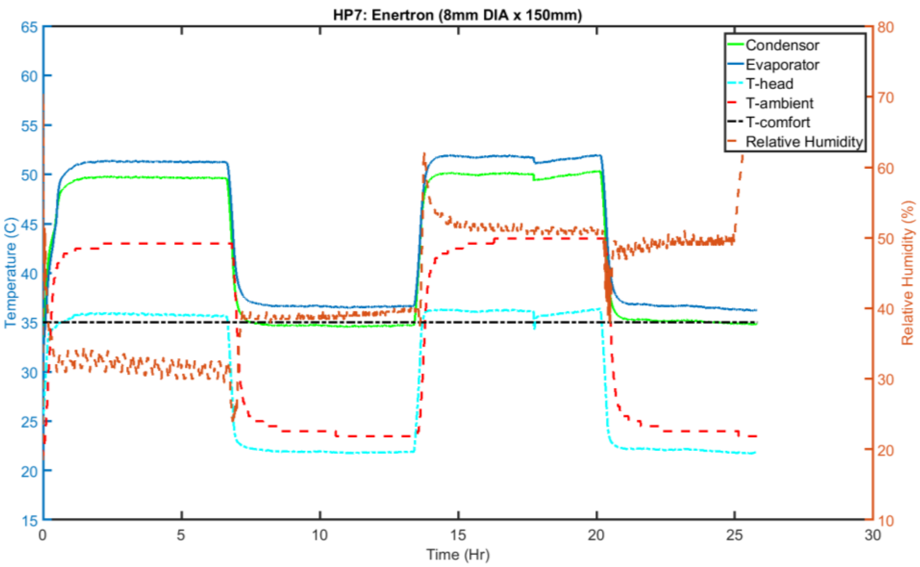


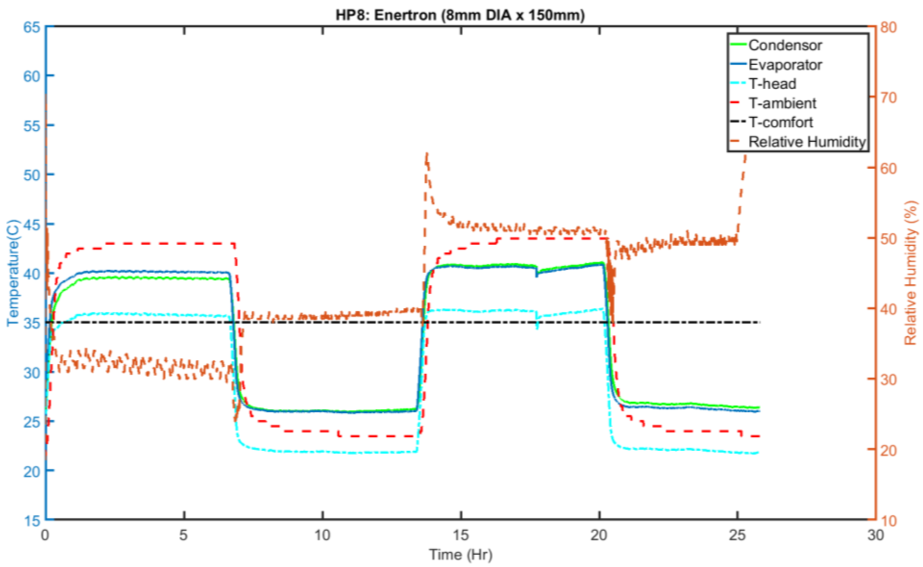


Los Alamos NATIONAL LABORATORY EST. 1943

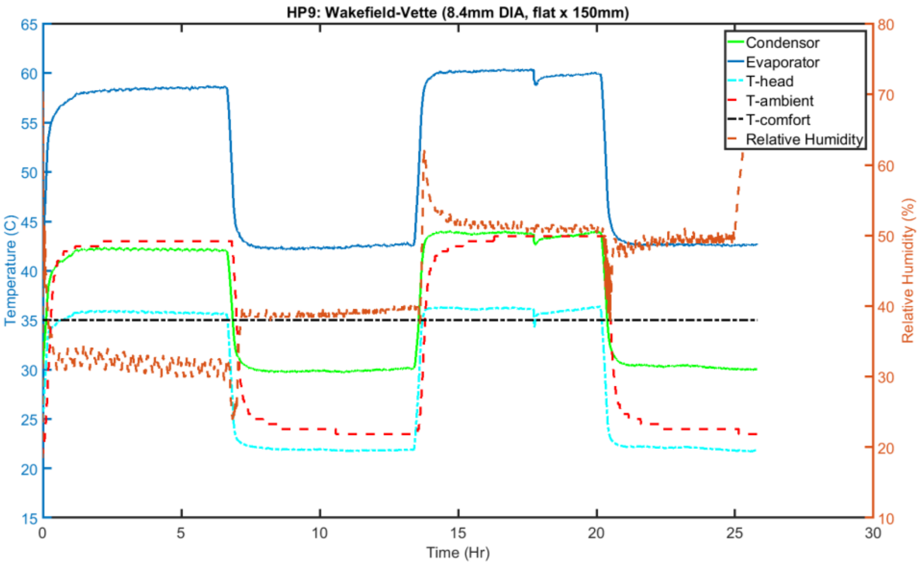
AET-1:17-077

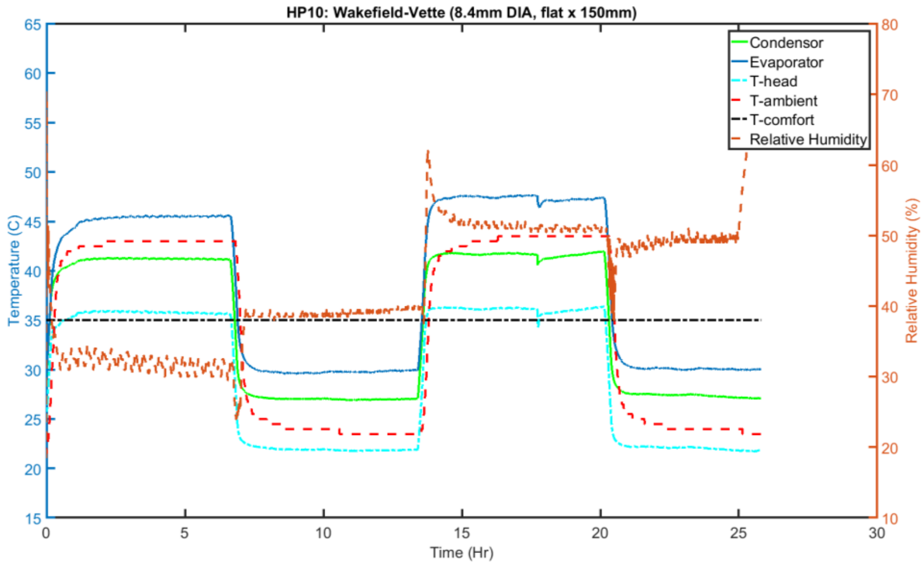
Environmental Tests per HP



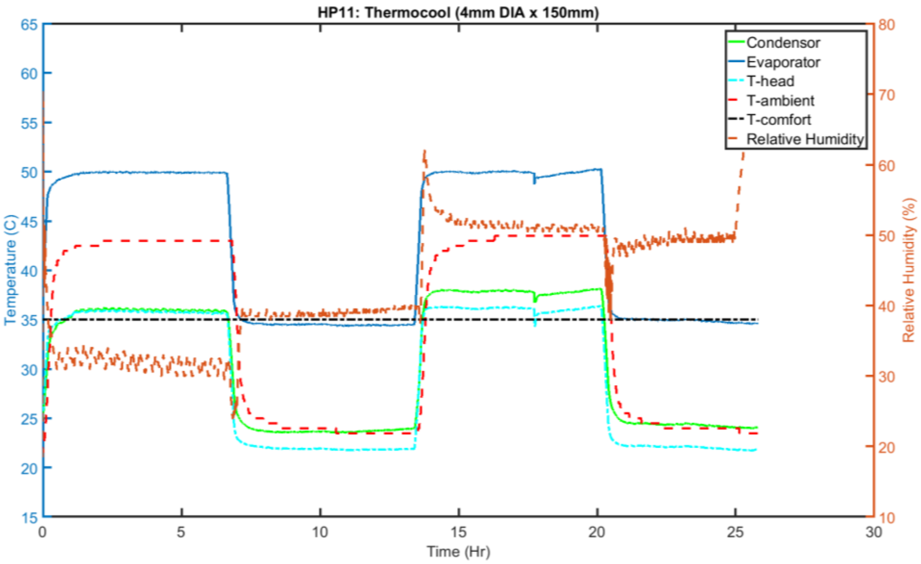


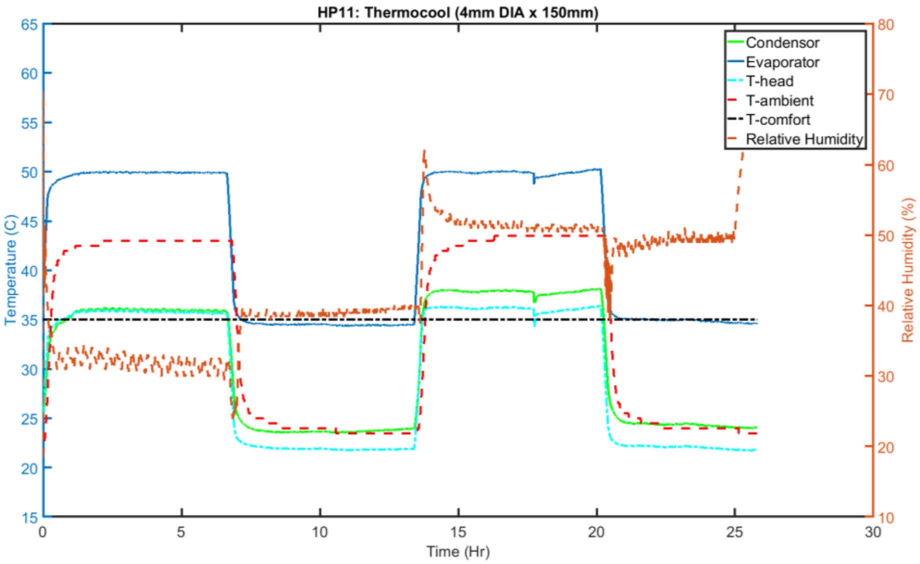
Environmental Tests per HP



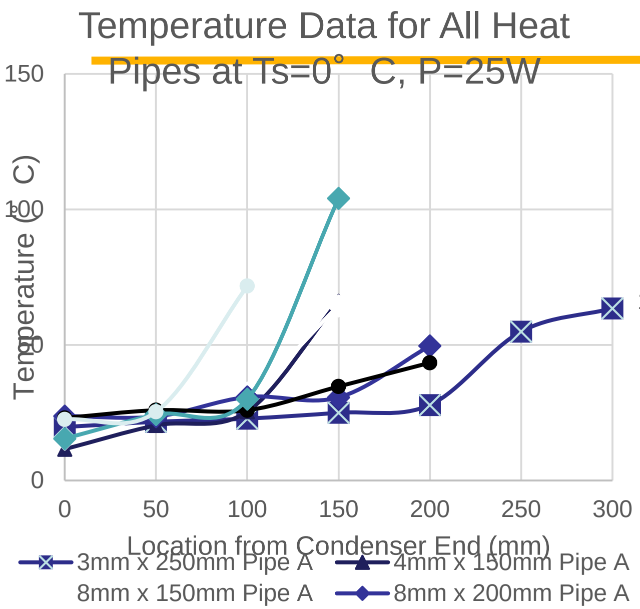


Environmental Tests per HP

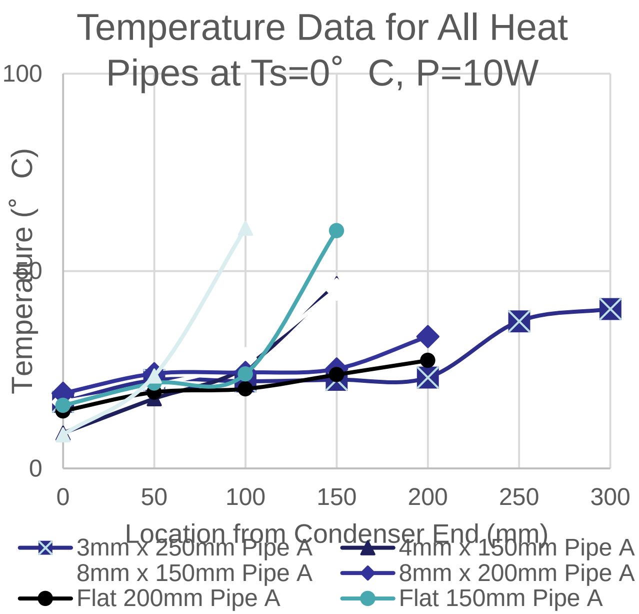




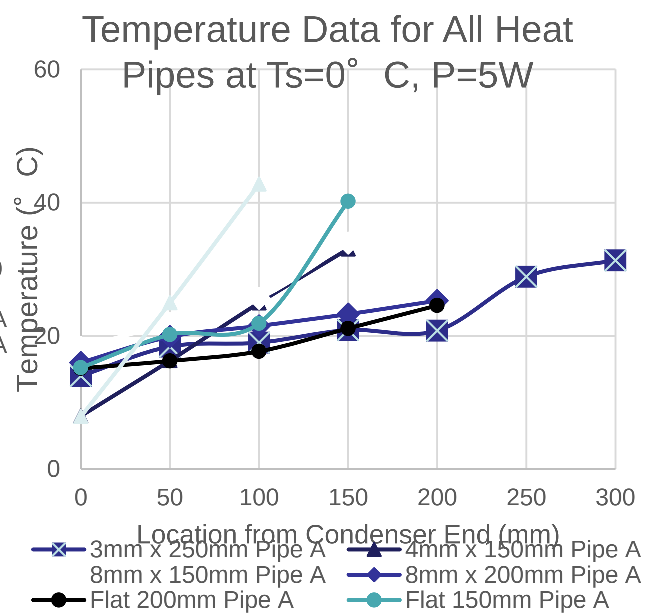
HEAT PIPE CALCULATIONS/ CHARACTERIZATION



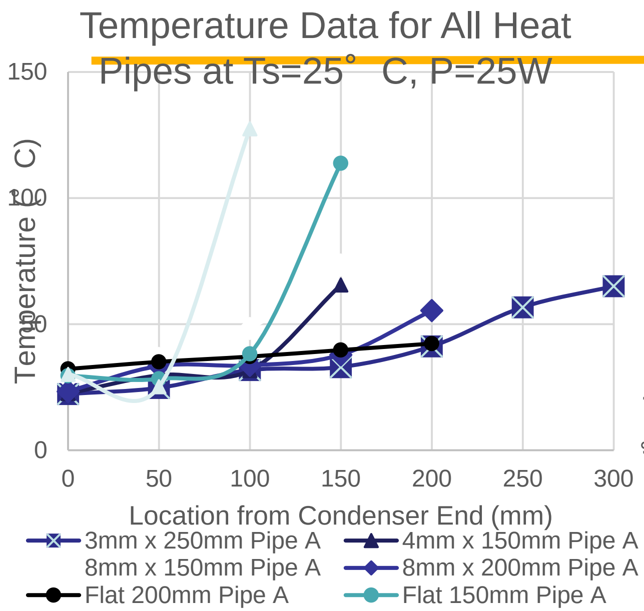
Temperature Data for All Heat Pipes at Ts=0° C, P=25W
150
100
50
0
Temperature (° C)
0
50
100
150
200
250
300
Location from Condenser End (mm)
3mm x 250mm Pipe A
4mm x 150mm Pipe A
8mm x 150mm Pipe A
8mm x 200mm Pipe A

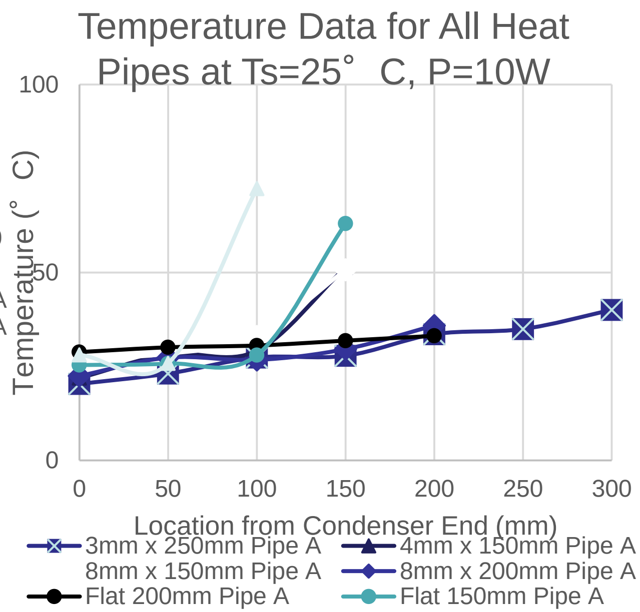


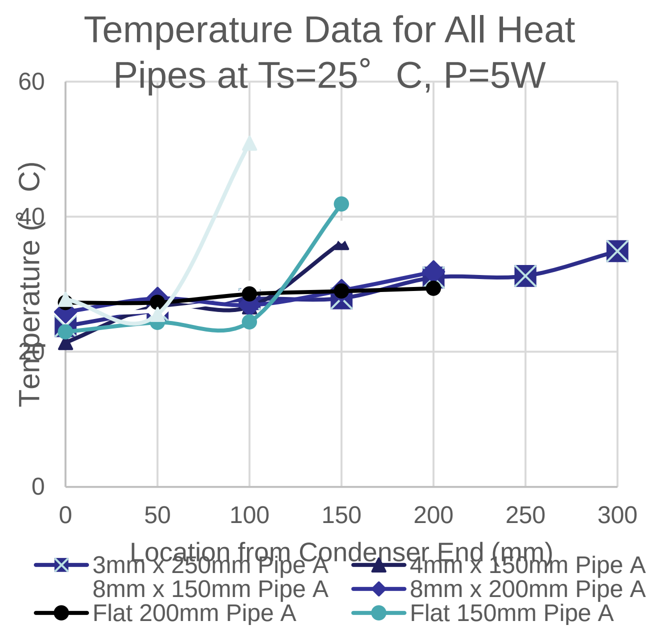
Temperature Data for All Heat Pipes at Ts=0° C, P=10W
100
50
0
Temperature (° C)
0
50
100
150
200
250
300
Location from Condenser End (mm)
3mm x 250mm Pipe A
4mm x 150mm Pipe A
8mm x 150mm Pipe A
8mm x 200mm Pipe A
Flat 200mm Pipe A
Flat 150mm Pipe A



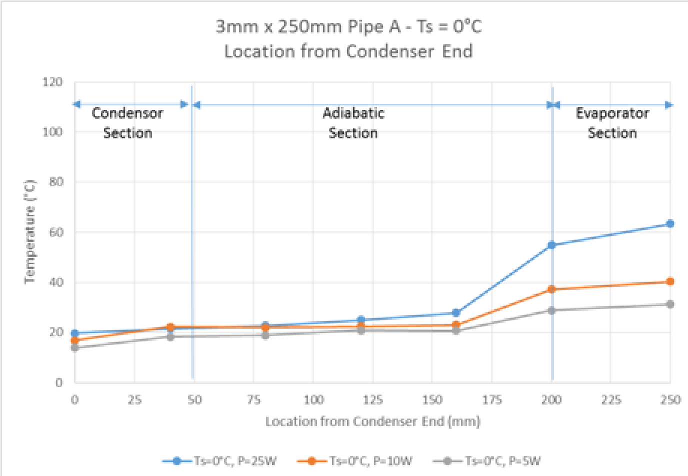
Temperature Data for All Heat Pipes at Ts=0° C, P=5W
60
40
20
0
Temperature (° C)
0
50
100
150
200
250
300
Location from Condenser End (mm)
3mm x 250mm Pipe A
4mm x 150mm Pipe A
8mm x 150mm Pipe A
8mm x 200mm Pipe A
Flat 200mm Pipe A
Flat 150mm Pipe A


Temperature Data for All Heat Pipes at Ts=25° C, P=25W
150
100
50
0
Temperature (° C)
0
50
100
150
200
250
300
Location from Condenser End (mm)
3mm x 250mm Pipe A
4mm x 150mm Pipe A
8mm x 150mm Pipe A
8mm x 200mm Pipe A
Flat 200mm Pipe A
Flat 150mm Pipe A

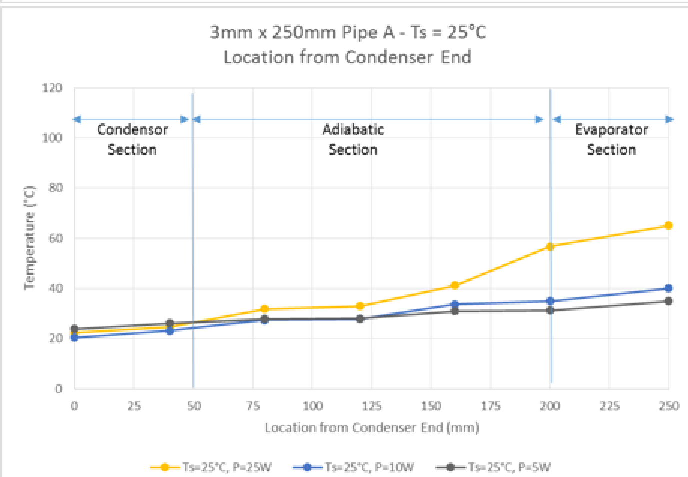

Temperature Data for All Heat Pipes at Ts=25° C, P=10W
100
50
0
Temperature (° C)
0
50
100
150
200
250
300
Location from Condenser End (mm)
3mm x 250mm Pipe A
4mm x 150mm Pipe A
8mm x 150mm Pipe A
8mm x 200mm Pipe A
Flat 200mm Pipe A
Flat 150mm Pipe A


Temperature Data for All Heat Pipes at Ts=25° C, P=5W
60
40
20
0
Temperature (° C)
0
50
100
150
200
250
300
Location from Condenser End (mm)
3mm x 250mm Pipe A
4mm x 150mm Pipe A
8mm x 150mm Pipe A
8mm x 200mm Pipe A
Flat 200mm Pipe A
Flat 150mm Pipe A

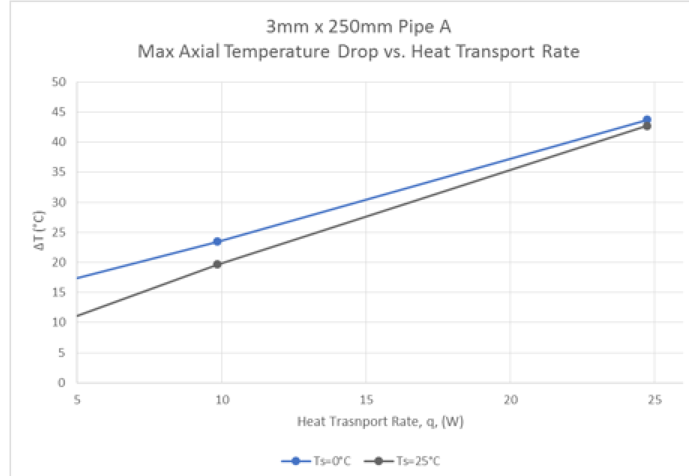
Heat Pipe 1 – Thermocool (3mm DIA x 250mm)



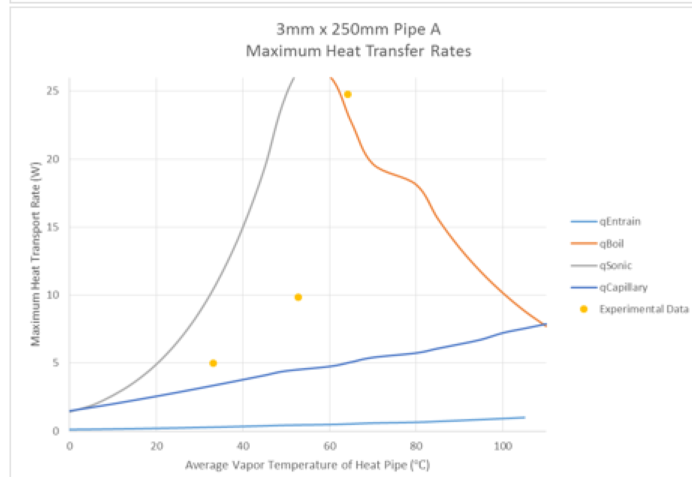
A.



B.



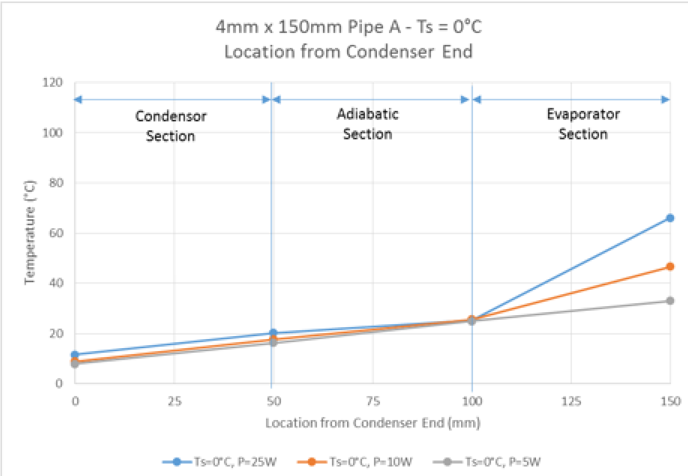
C.



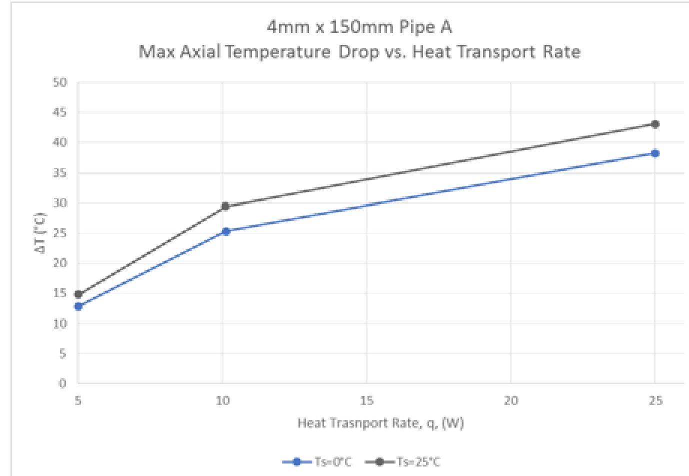
D.

Heat Pipe 2 – Thermocool (4mm DIA x 150mm)

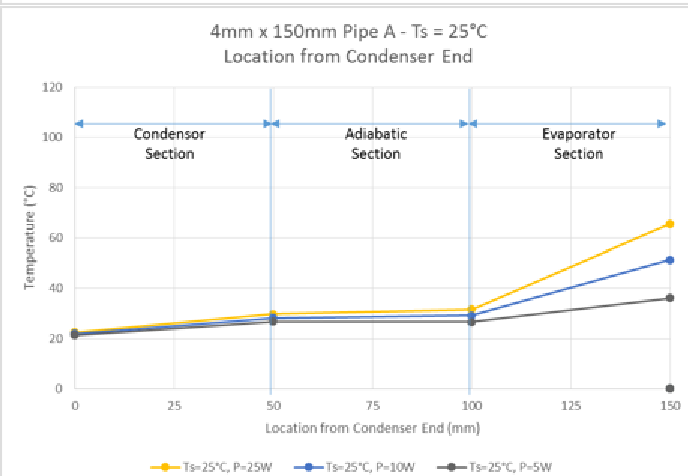
A.



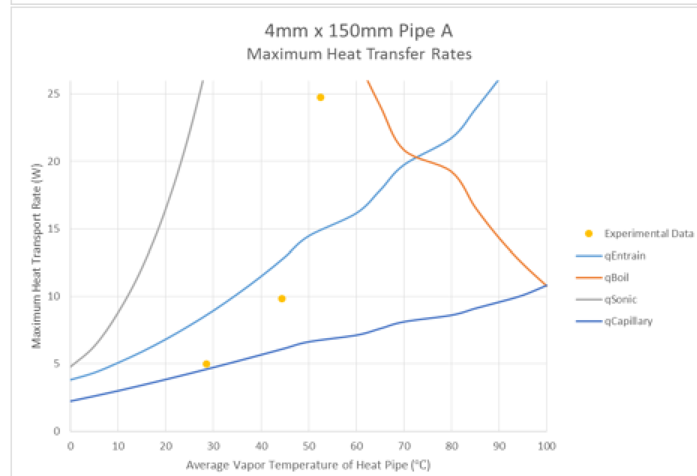
C.



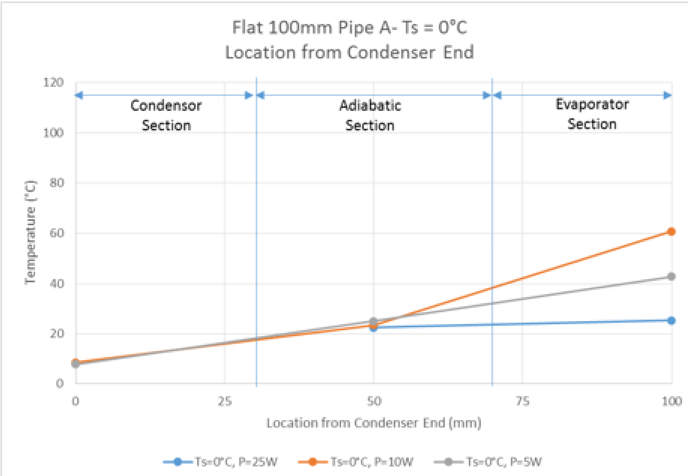
B.



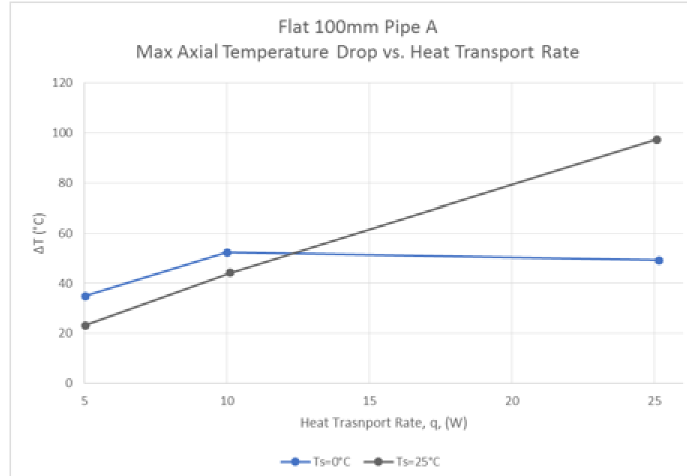
D.



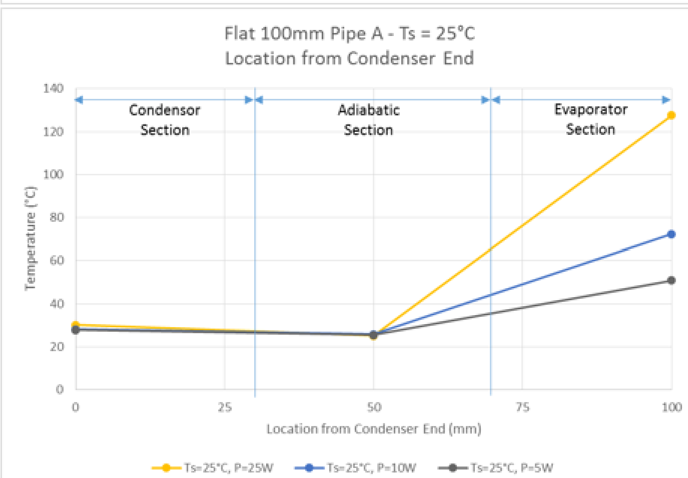
Heat Pipe 3 – Wakefield-Vette (8.4mm DIA x 2.5mm T x 100 mm L)



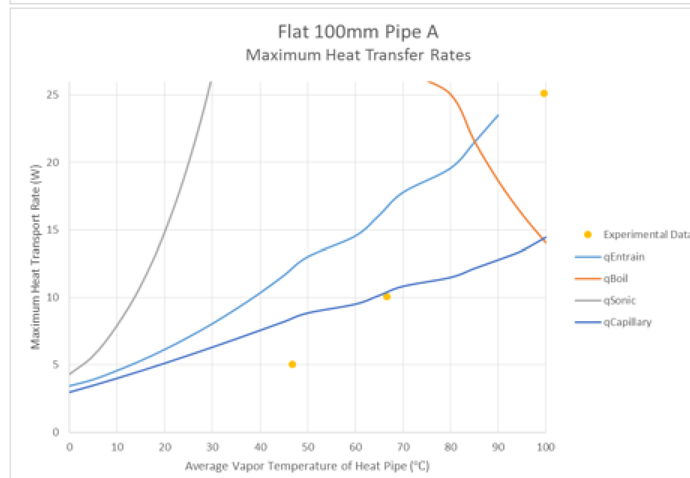
A.



C.

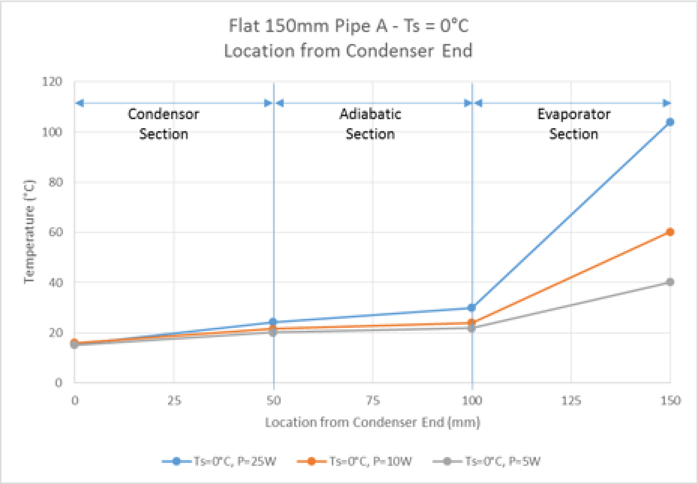


B.

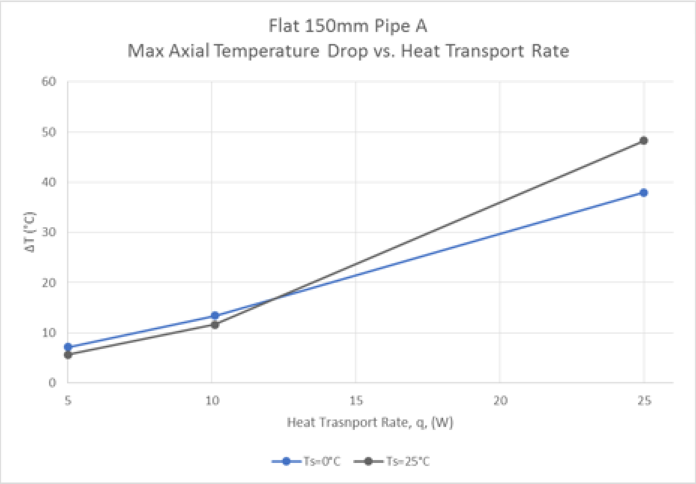


D.

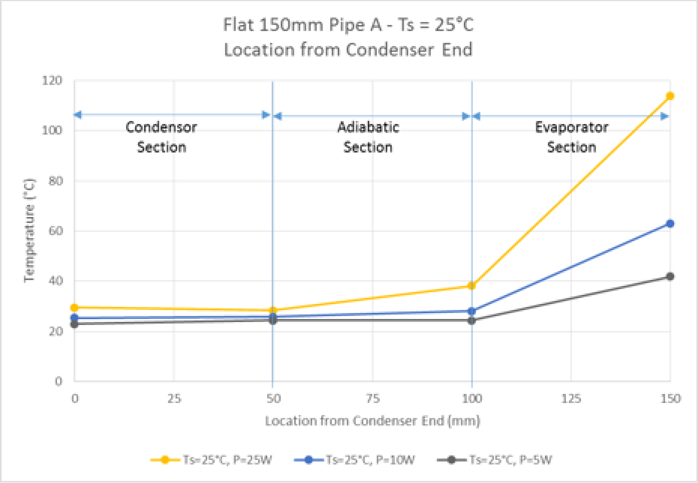
Heat Pipe 4 – Wakefield-Vette (8.4mm DIA x 2.5mm T x 150 mm L)



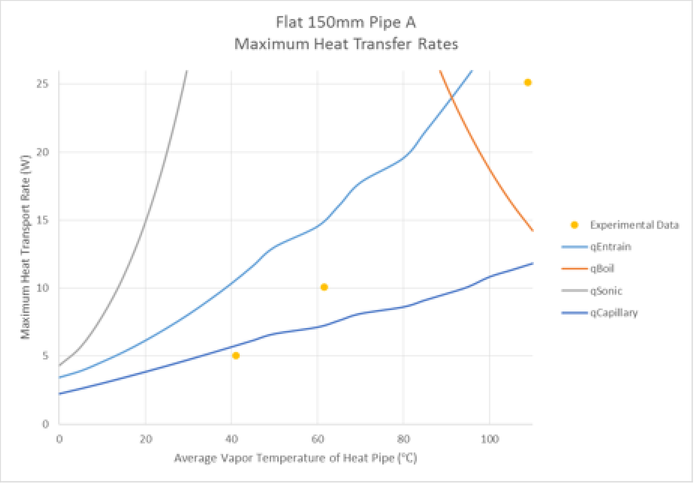
A.



C.



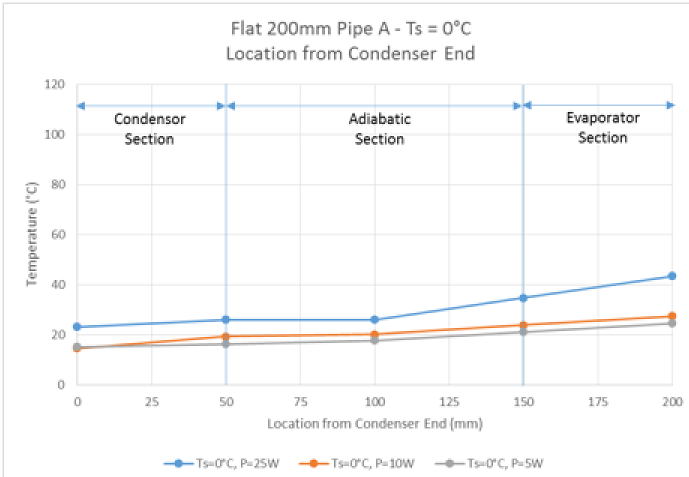
B.



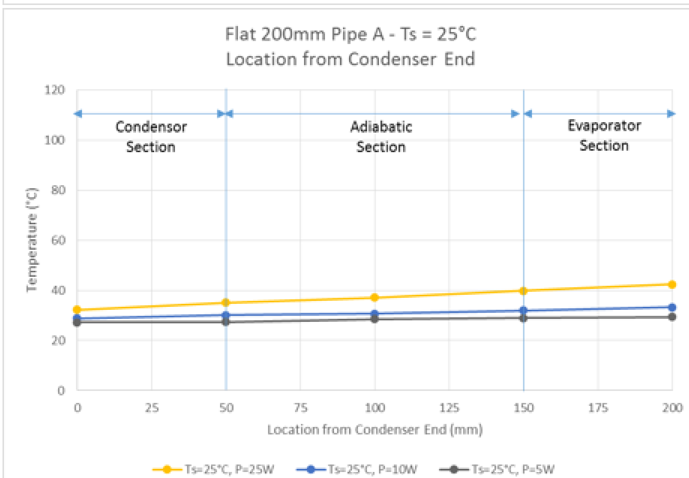
D.

Heat Pipe 5 – Wakefield-Vette (8.4mm DIA x 2.5mm T x 200 mm L)

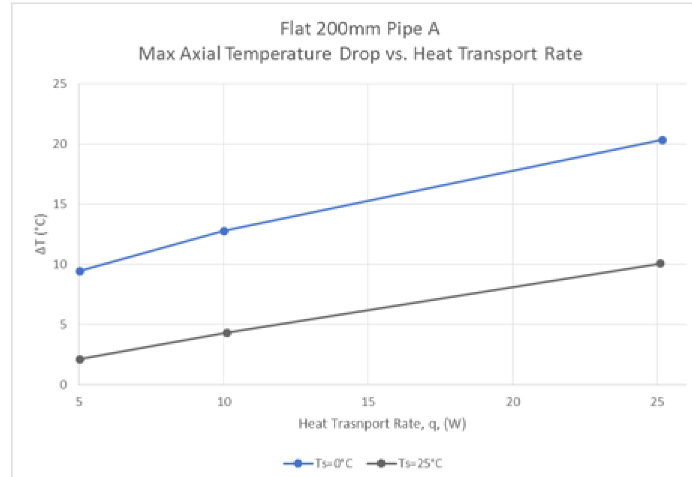
A.



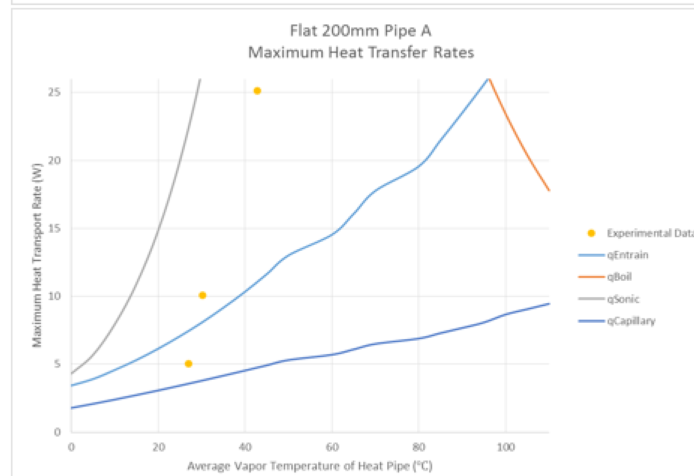
B.



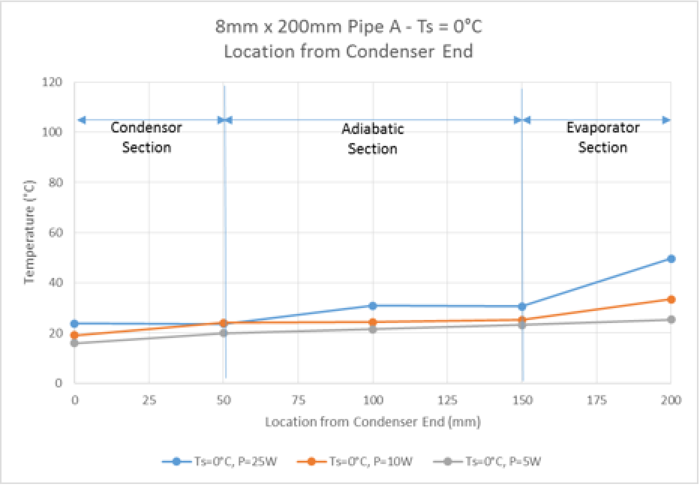
C.



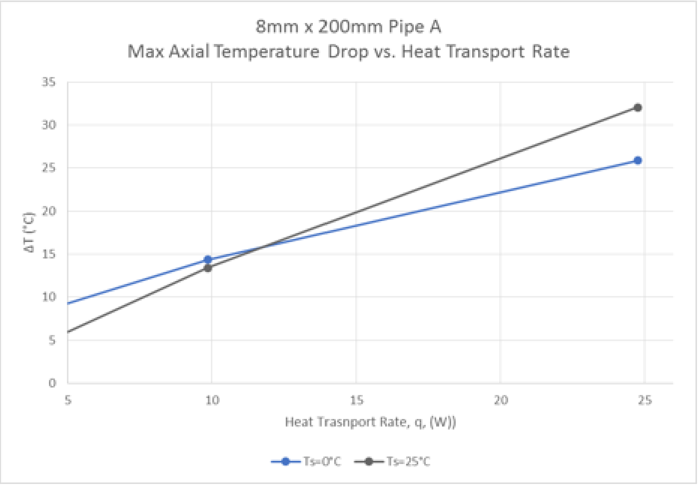
D.



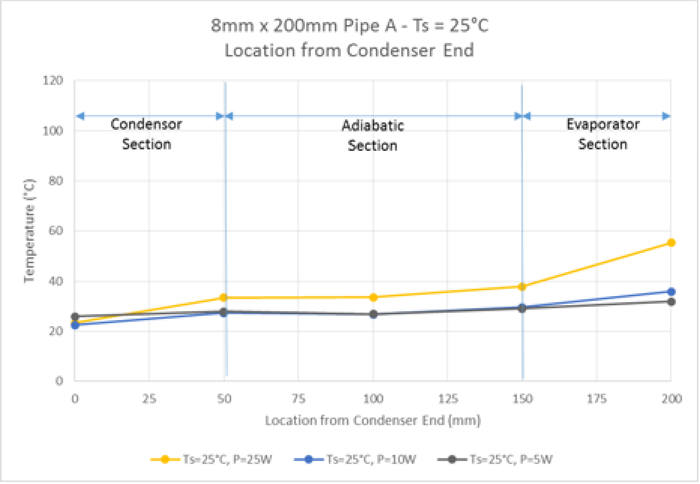
Heat Pipe 6 – Enertron (8mm DIA x 200mm)



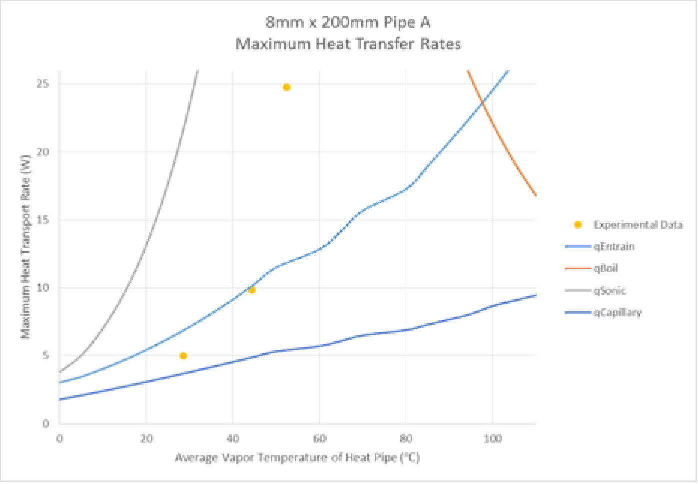
A.



C.

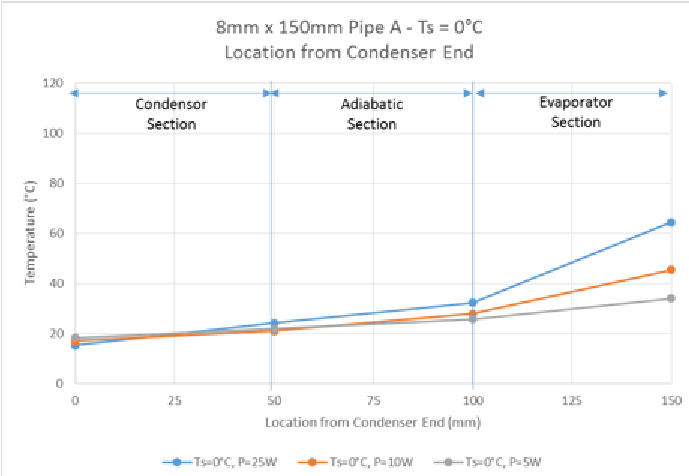


B.

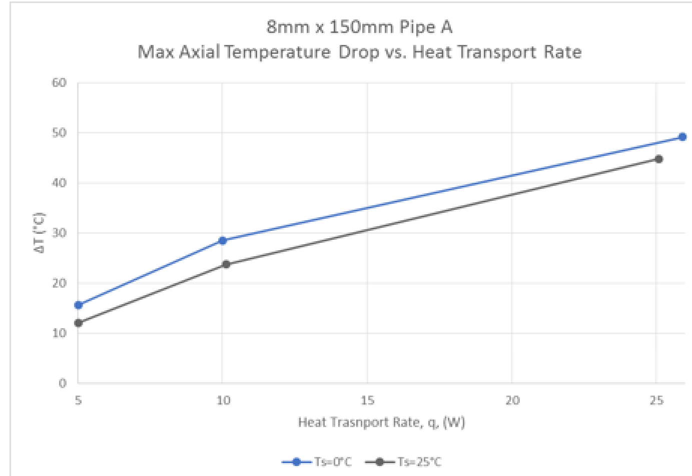


D.

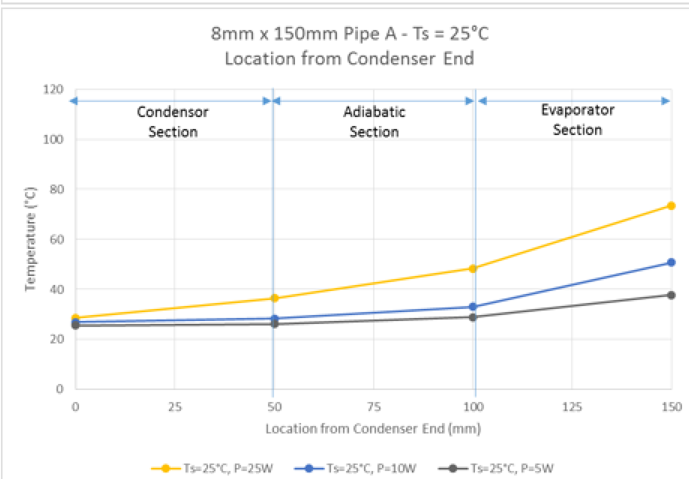
Heat Pipe 7 – Enertron (8mm DIA x 150mm)



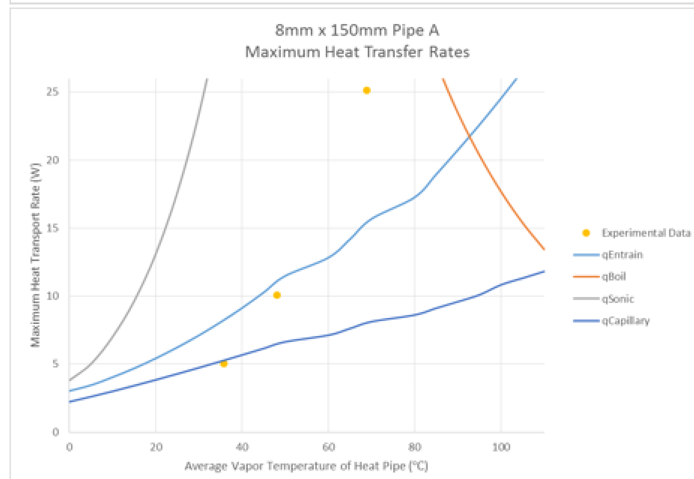
A.



C.



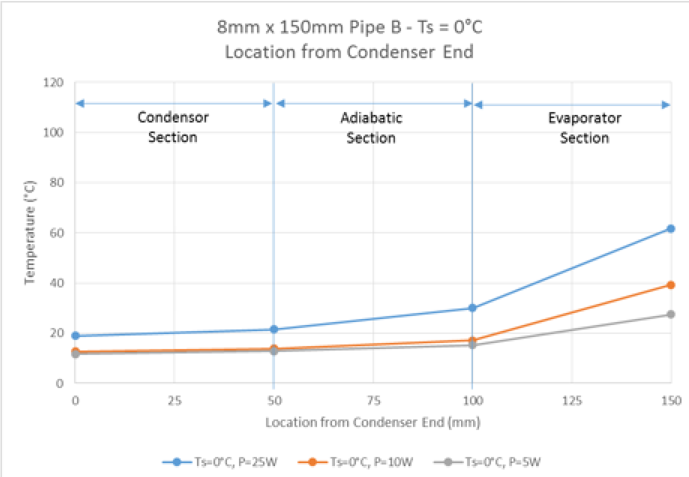
B.



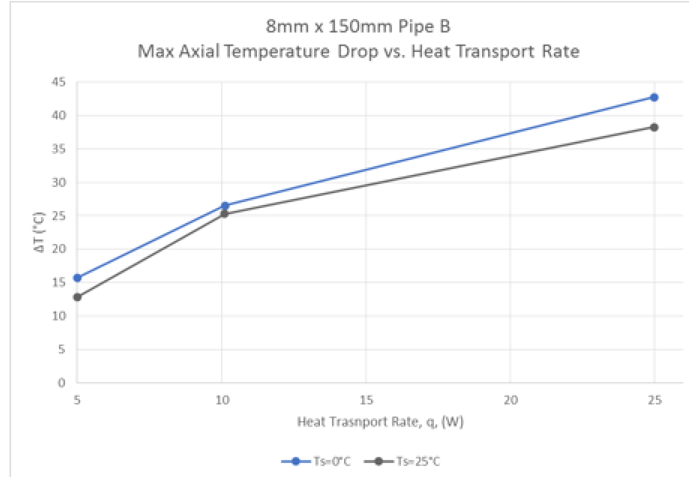
D.

Los Alamos NATIONAL LABORATORY EST. 1943

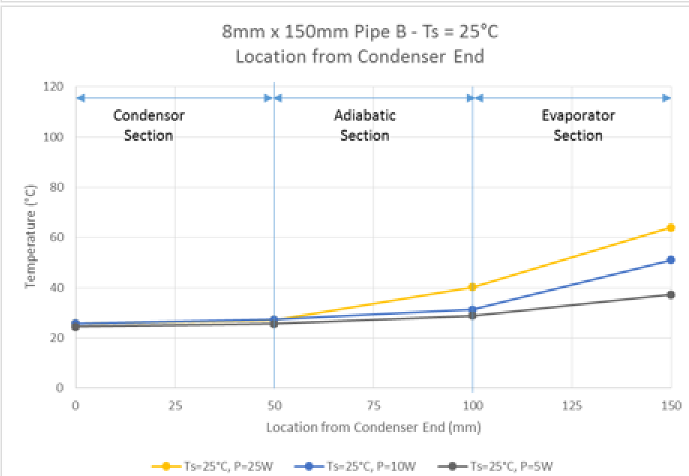
Heat Pipe 8 – Enertron (8mm DIA x 150mm)



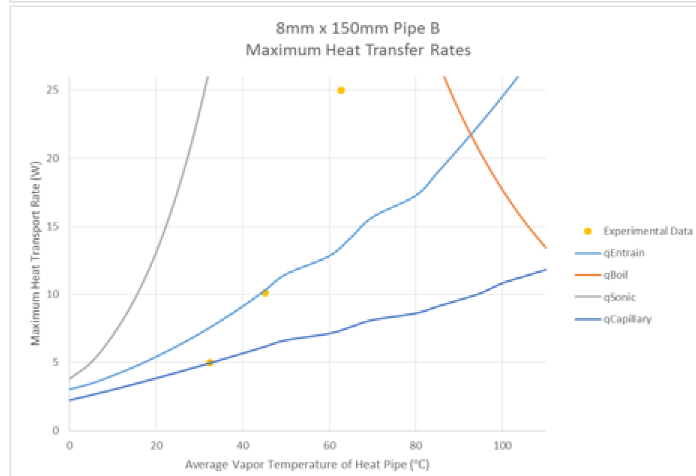
A.



C.



B.



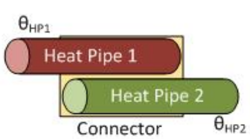
D.

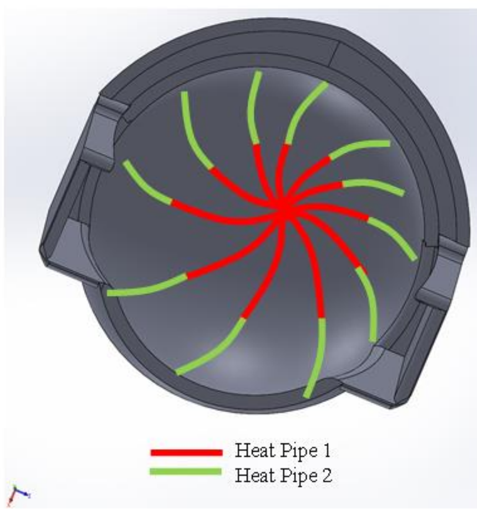
Heat Pipe Calculations

Problem Definition

In order to move the heat from the head of the helmet - wearer, heat pipes will be installed inside the helmet, to connect with the wicking material. Designs for the heat pipes have been laid out previously in the HEHV systems-model. The calculations here are to show the heat pipe physics and account of the minimum requirements to move heat.

The heat pipes must move heat from the heat to the sides of the helmet. It is assumed that the heat pipes will use gravity assist to provide the maximum efficiency. The pipes themselves will be circular pipes, utilizing capillary pressure differences to performthe heat transfer.





Assumptions

1. Steady- state conditions
2. One-Dimensional conduction along the length of the heat pipes
3. Effectiveness of the connector is 1, all heat from HP1 goes into HP2, where $\theta_{HP1} = \theta_{HP2}$
4. There is perfect wetting of heat pipe (θ=1) using water as the fluid
5. The origin of the pipes is at the center of the helmet so all pipes are of equal distance for now
6. Gravity assitive pipes are used in the system, of no greater than 0.1524 [m] (6 [in]) in length
7. Material : Copper-alloy with the following properties for shell and wick:

Properties of Outline Row 3: Copper Alloy

	A	B	
1	Property	Value	
2	Density	8300	kg m^-3
3	Isotropic Secant Coefficient of Thermal Expansion		
4	Coefficient of Thermal Expansion	1.8E-05	C^-1
5	Zero-Thermal-Strain Reference Temperature	22	C
6	Isotropic Elasticity		
7	Derive from	Young's Modulus and Poisson's Ratio	
8	Young's Modulus	1.1E+11	Pa
9	Poisson's Ratio	0.34	
10	Bulk Modulus	1.1458E+11	Pa
11	Shear Modulus	4.1045E+10	Pa
12	Tensile Yield Strength	2.8E+08	Pa
13	Compressive Yield Strength	2.8E+08	Pa
14	Tensile Ultimate Strength	4.3E+08	Pa
15	Compressive Ultimate Strength	0	Pa
16	Isotropic Thermal Conductivity	401	W m^-1 C^-1
17	Specific Heat	385	J kg^-1 C^-1
18	Isotropic Relative Permeability	1	
19	Isotropic Resistivity	Tabular	

EES Calculations

```
T=25 [C] "Atmospheric temperature - [C]"
P=101 [kPa] "Atmospheric pressure - [kPa]"
g=9.81 [m/s^2] "Gravity - [m/s^2]"
sigma=surfacetension(Water,T=T) "Water surface tension at T = 25 [C]  - [N/m]"
rho=density(Water,T=T,P=P) "Water density at T = 25 [C], atmospheric conditions - [kg/m^3] "
theta = 1 [deg] "Wetting angle - assumed perfect conditions - [deg]"

H_HP1=0.1016 [m] "Heat pipe 1 height - [m]"
H_HP2=0.1524 [m] "Heat pipe 2 height - [m]"

r_eff_HP1=(2*sigma)/(rho*g*H_HP1) "Porosity radius of wicking material in HP1 - [N - s^2/kg]"
r_eff_HP2=(2*sigma)/(rho*g*H_HP2) "Porosity radius of wicking material in HP1 - [N - s^2/kg]"

P_HP1=(2*sigma*cos(theta))/(r_eff_HP1) "Capillary pressure difference over the length of HP1 - [Pa]"
P_HP2=(2*sigma*cos(theta))/(r_eff_HP2) "Capillary pressure difference over the length of HP2 - [Pa]"
```

Unit Settings: SI C kPa kJ mass deg

$g = 9.81$ [m/s^2]	$H_{HP1} = 0.1016$ [m]	$H_{HP2} = 0.1524$ [m]
$P = 101$ [kPa]	$\boxed{P_{HP1} = 993.6}$ [Pa]	$\boxed{P_{HP2} = 1490}$ [Pa]
$\rho = 997.1$ [kg/m^3]	$\boxed{r_{eff,HP1} = 0.0001448}$ [N-s^2/kg]	$\boxed{r_{eff,HP2} = 0.00009656}$ [N-s^2/kg]
$\sigma = 0.07197$ [N/m]	$T = 25$ [C]	$\theta = 1$ [deg]

The porosity of the wicking material for the heat pipes is approximately 96 [um] and 144 [um], meaning they can be printed on the Sigma Nanoscribe. However, we still need to consider how to seal the heat pipes if we go the AM route.